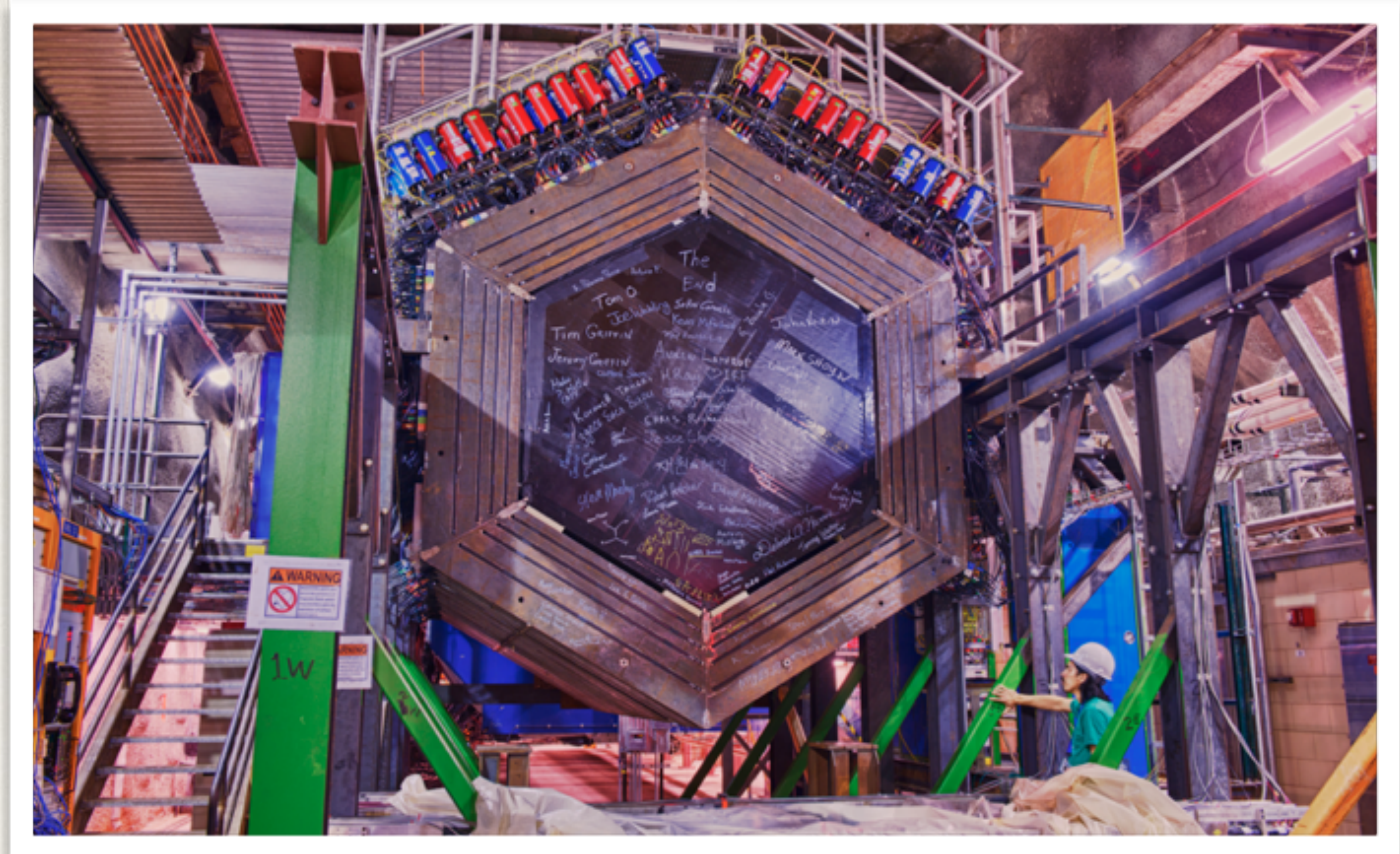


Cross Sections and What They Tell Us

IF Summer Student Lecture Series

Laura Fields, Northwestern

10 July 2014

Introduction

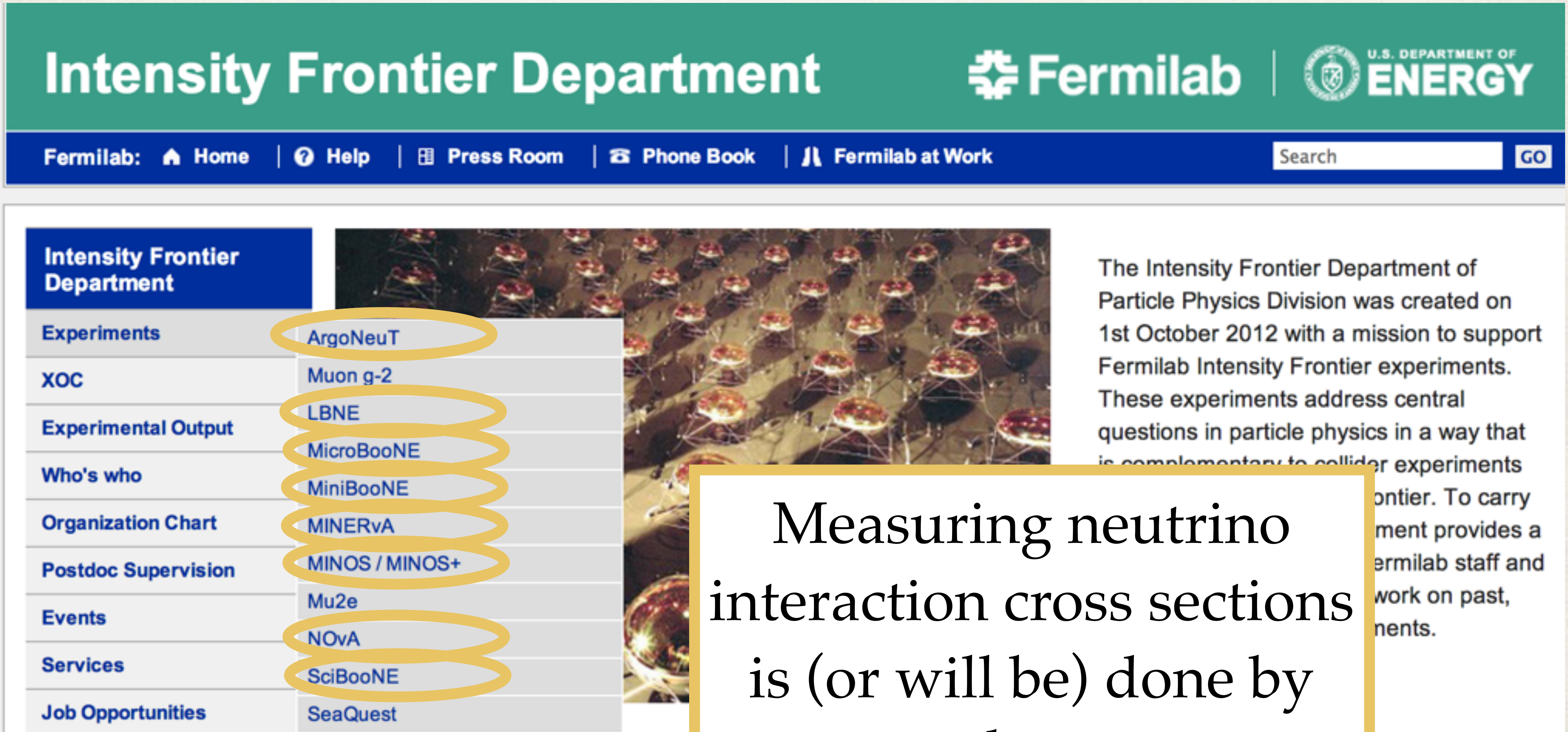
"The biggest change I've noticed since starting grad school is that I no longer feel encumbered by my own ignorance. I mean, I'm still ignorant — I just realized everyone else is too."

- Unknown postdoc

Please ask questions!

Now or later (laurajfields@gmail.com)

Introduction



Measuring neutrino interaction cross sections is (or will be) done by ALL of the Intensity Frontier neutrino experiments

Introduction

- In this talk:
  - What is a cross section?
  - Why do we expend so much effort measuring neutrino cross sections?
  - What types of cross sections are we trying to measure?
  - (Selected) Cross section experiments and their recent measurements
    - MiniBooNE
    - MINERvA
    - Liquid Argon Detectors: ArgoNeuT and MicroBooNE

Introduction

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These mostly don't depend on each other, so if you fall asleep for one, you'll hopefully still understand the next ones

Introduction

- What exactly do we mean by a cross section?

Introduction

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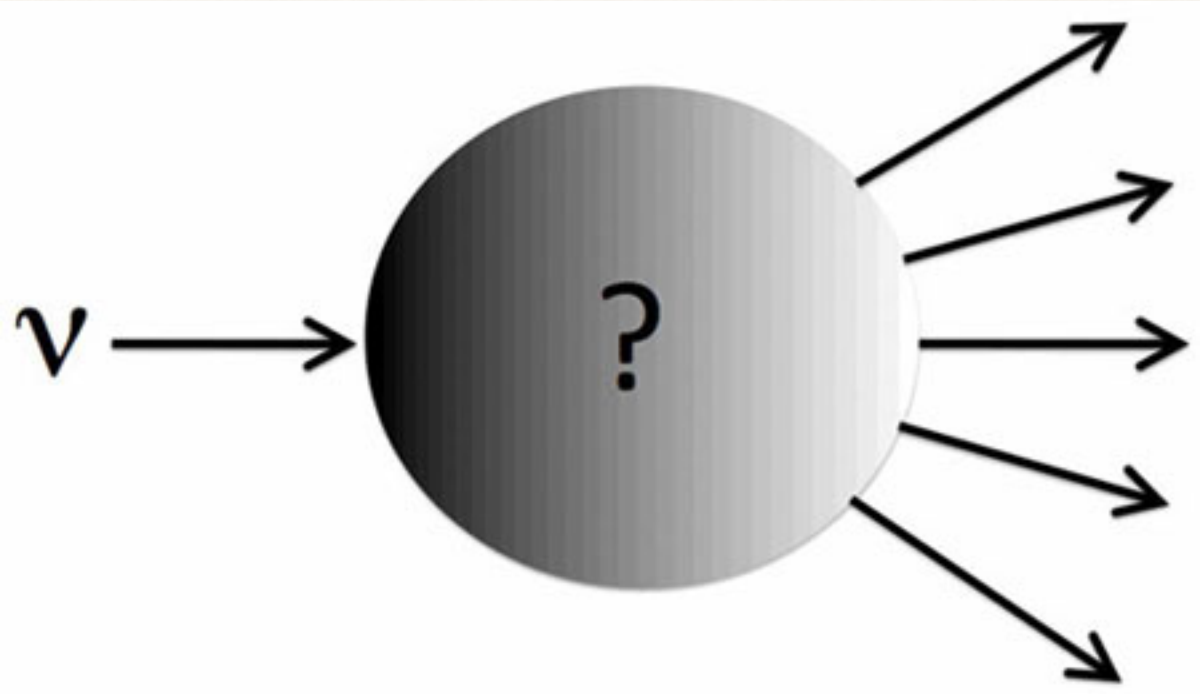

http://www.int.washington.edu/

Cross sections are a measure of the probability that a some type of interaction will occur given some particle incident a target.

In this talk, the particle in question is a neutrino, and the targets are neutrino detectors.

Introduction

- What exactly do we mean by a cross section?

Cross section

Number of Targets

(e.g. number of nucleons in the detector)

$$\text{Number of Interactions} = \sigma \times \Phi \times N$$

Neutrino Flux

A measure of the number of neutrinos incident on the detector

The number of interactions in a neutrino detector is proportional to the interaction cross section, the neutrino flux and the number of targets in the detector

Introduction

- What exactly do we mean by a cross section?

$$\text{Number of Interactions} = \sigma \times \Phi \times N$$

Can be calculated theoretically (in some cases)
Neutrino interactions are (as far as we know)
completely described by the standard model

Or measured experimentally

$$\sigma = \frac{\text{Number of Interactions}}{\Phi \times N}$$

Introduction

- What exactly do we mean by a cross section?

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Can be calculated theoretically (in some cases)
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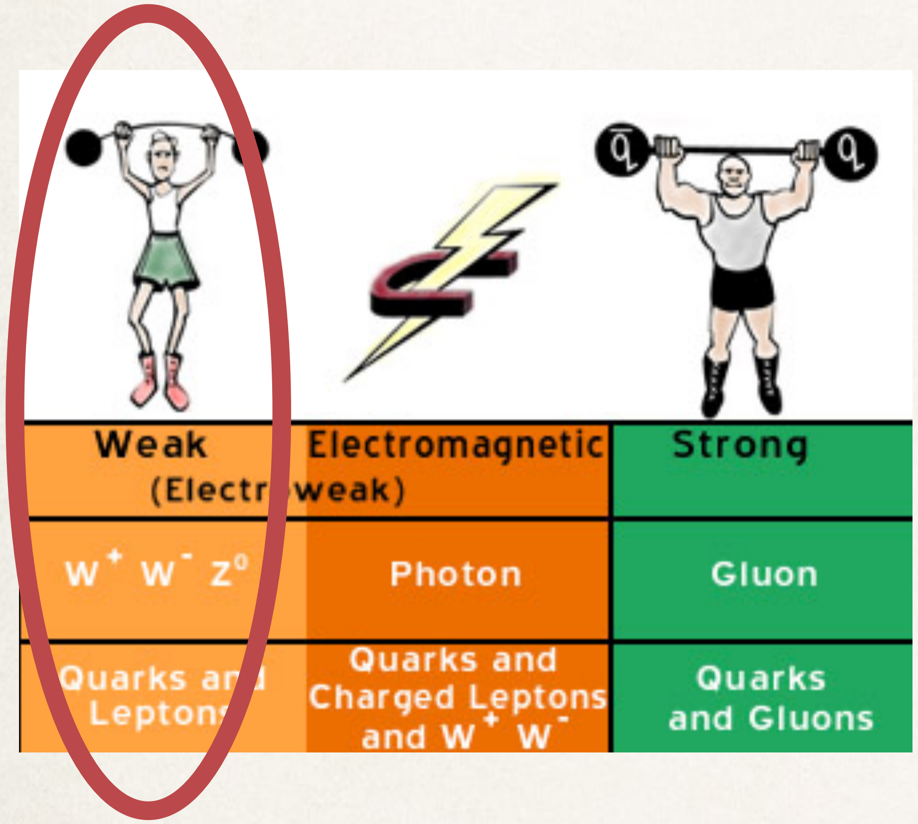
completely described by the standard model

I won't cover a lot of theory today. When you take Quantum Field Theory, you'll spend a lot of time calculating cross sections.

This article: Rev. Mod. Phys. 84, 1307 (2012) (http://arxiv.org/abs/1305.7513) is a good place to start for a neutrino-interaction-specific discussion of cross section calculations.

Introduction

- Neutrino cross sections are **very small**



Neutrinos interact only via the weak force, which is called "weak" for a reason!

The cross section for a few MeV neutrino interacting with a proton is ~5 x 10^{-44} cm^2

Nearly 20 orders of magnitude smaller than interaction cross section of a photon (~10^{-25} cm^2)!

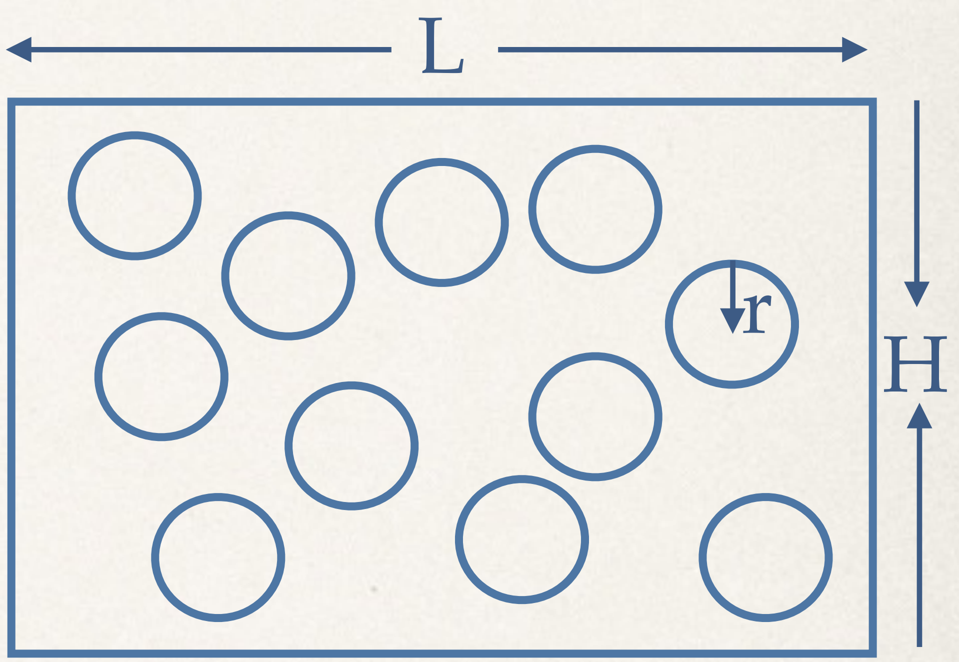
Corresponds to a mean free path in steel of ~10 light years

Introduction

- Wait, why does a probability have units of area?

It is convenient to view interaction probabilities as an effective area

Consider a classical system — e.g. a dart board with n circles.

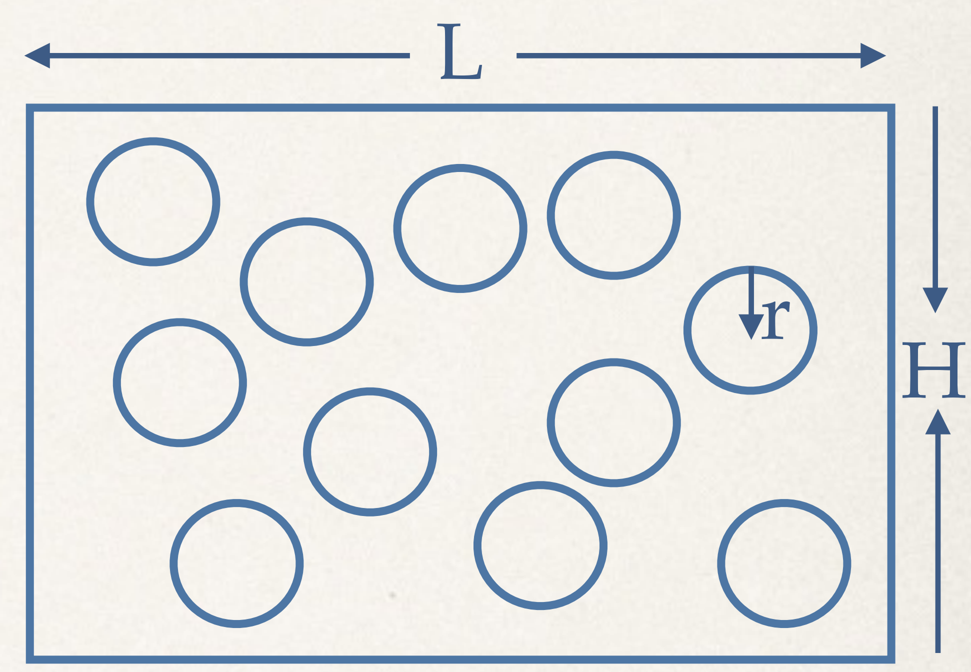


- If you throw your dart at a random point on the board, what is the probability that the dart will hit a circle? (in terms of n, L, H and r)

Introduction

- Wait, why does a probability have units of area?

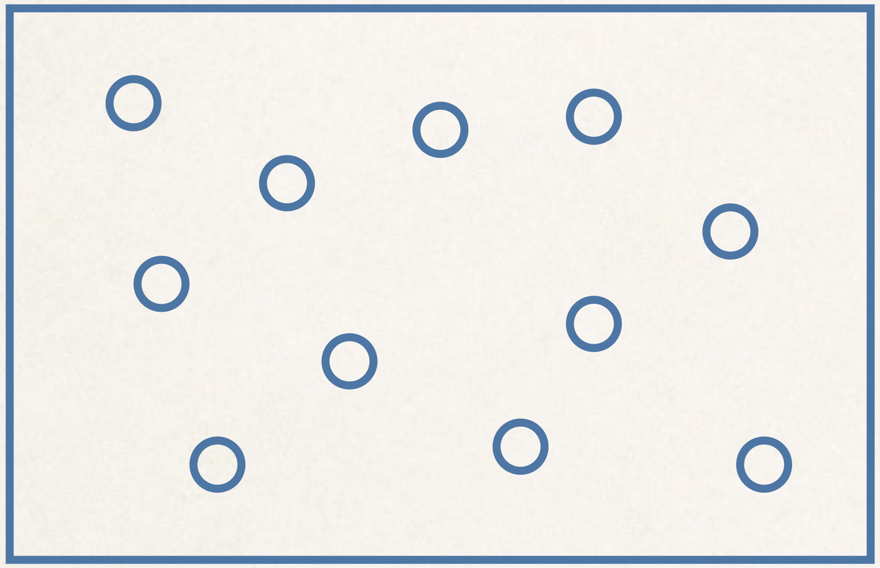
$$P_{\text{circle}} = \frac{\text{Area of Circles}}{\text{Area of Page}} = \frac{n\pi r^2}{LH}$$



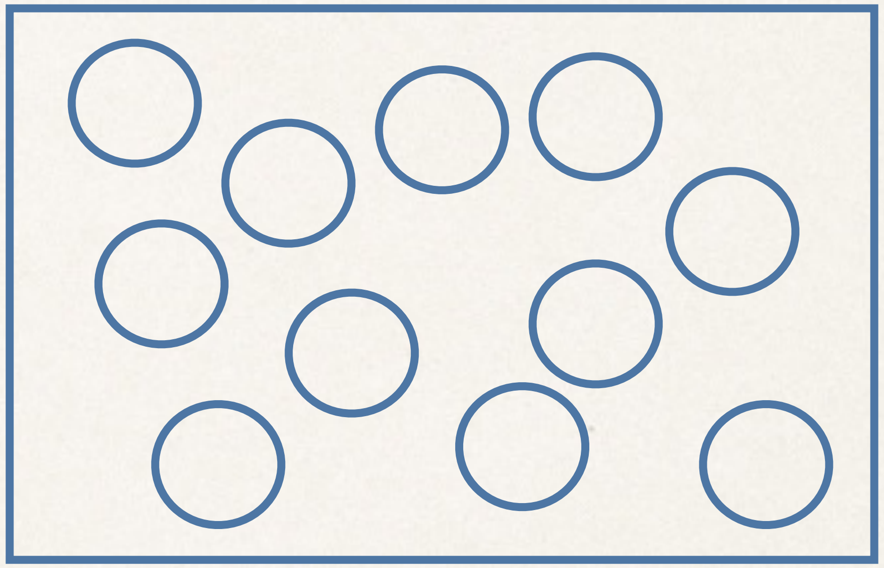
- The probability of your dart "interacting" with a circle is proportional to the area (or "cross section") of the circles.

Introduction

- Wait, why does a probability have units of area?



Small cross section =
small probability of interaction



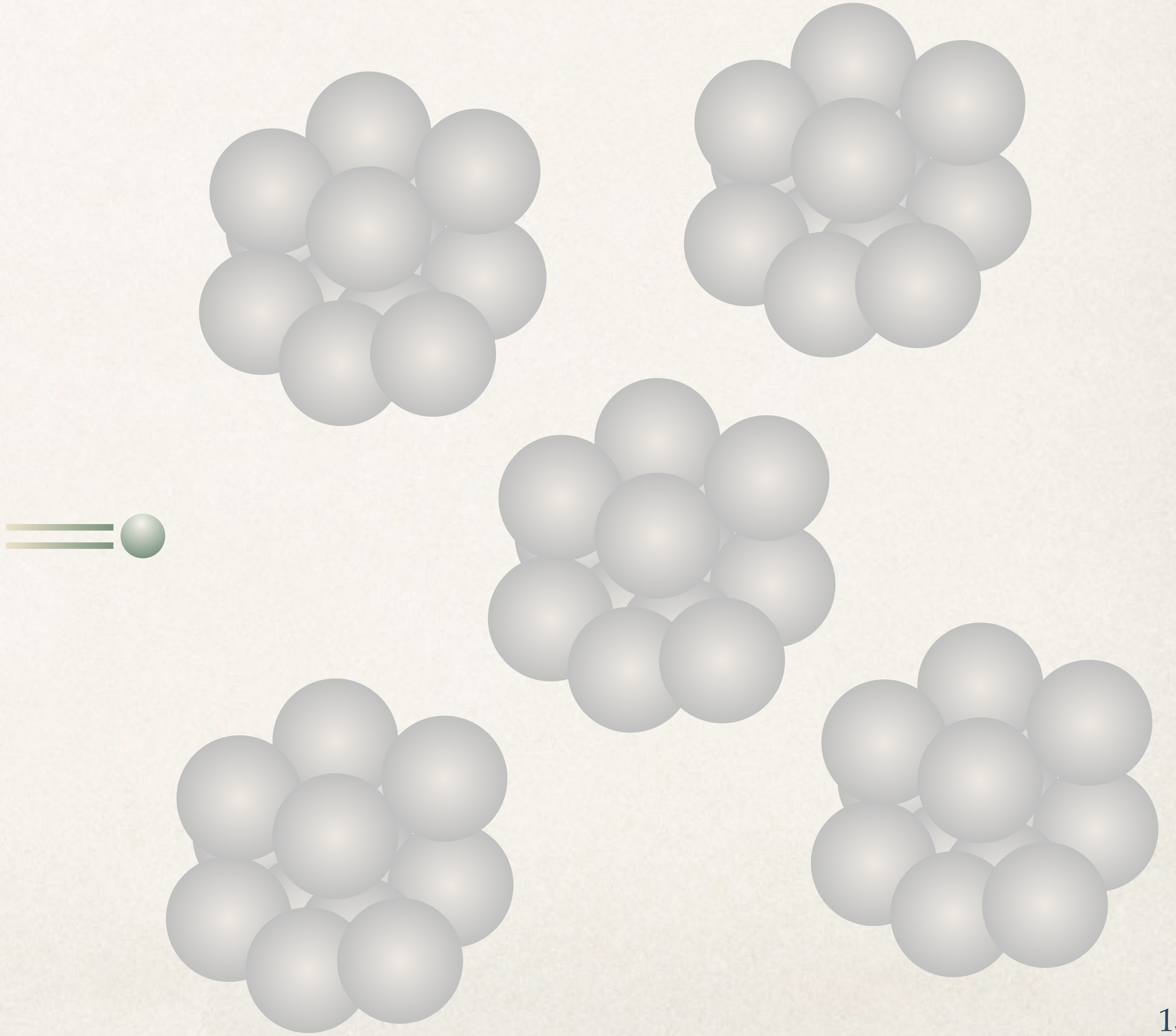
Large cross section =
large probability of interaction

Introduction

- Wait, why does a probability have units of area?

Of course, this analogy breaks down when you move to the quantum world of particle interactions, which don't behave like darts hitting a board

But we still use the word cross section to describe the probability of interaction



Why We Care About Cross Sections

Why We Care About Cross Sections

- The primary reason to measure neutrino cross sections is that they are a key ingredient in answering the big questions of neutrino physics

The experimental situation

- Absolute mass / nature of the neutrino
- Neutrino oscillations
- Sterile neutrinos?

These were nicely summarized in Mark Messier's talk in this series on June 19th

Why We Care About Cross Sections

- In particular, you heard that many of the questions modern neutrino physics aims to answer relate to neutrino oscillations:

Weak Interaction States

Mass States

$$\begin{vmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{matrix}\right\rangle = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \left|\begin{matrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{matrix}\right\rangle$$

$$P_{\alpha\beta} = \sin^2(2\theta)\sin^2\left(1.27\Delta m^2\ [\mathrm{eV}^2]\frac{L\ [\mathrm{km}]}{E\ [\mathrm{GeV}]}\right)$$

$\lvert\Delta m^2_{32}\rvert \equiv \lvert m^2_3 - m^2_2\rvert \simeq 2\times10^{-3}\ \mathrm{eV}^2$	$\Delta m^2_{31} \simeq \Delta m^2_{32}$	$\Delta m^2_{21} \simeq 8\times10^{-5}\ \mathrm{eV}^2$
$\nu_\mu \to \nu_\mu$ $\nu_\mu \to \nu_\tau$	$\nu_e \to \nu_e$ $\nu_\mu \to \nu_e$	$\nu_e \to \nu_e$ $\nu_e \to \nu_\mu + \nu_\tau$
atmospheric and long baseline	reactor and long baseline	solar and reactor
$\theta_{23} \simeq 45^\circ$	$\theta_{13} = 9^\circ$	$\theta_{12} \simeq 35^\circ$

M. Messier

The current neutrino standard model contains three weak-interaction neutrino eigenstates that are mixtures of three different neutrino mass states

Why We Care About Cross Sections

- In particular, you heard that many of the questions modern neutrino physics aims to answer relate to neutrino oscillations:

Weak Interaction States

Mass States

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$$P_{\alpha\beta} = \sin^2(2\theta)\sin^2\left(1.27\Delta m^2\ [\mathrm{eV}^2]\frac{L\ [\mathrm{km}]}{E\ [\mathrm{GeV}]}\right)$$

This means that a neutrino of one flavor (e, μ or τ) will appear to oscillate to other flavors

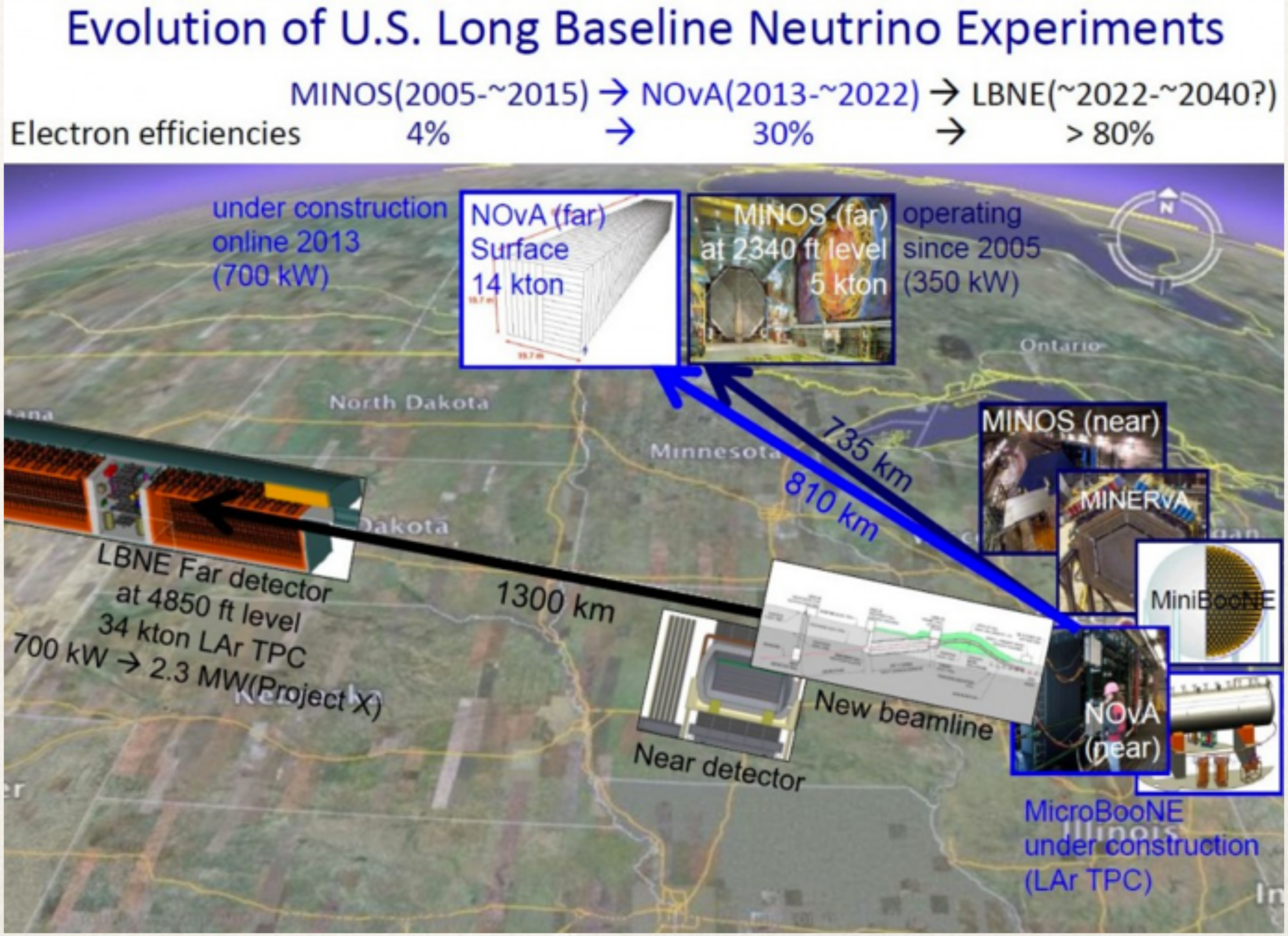
The probability of oscillation is a function of the neutrino's energy and the distance it travels

M. Messier

The current neutrino standard model contains three weak-interaction neutrino eigenstates that are mixtures of three different neutrino mass states

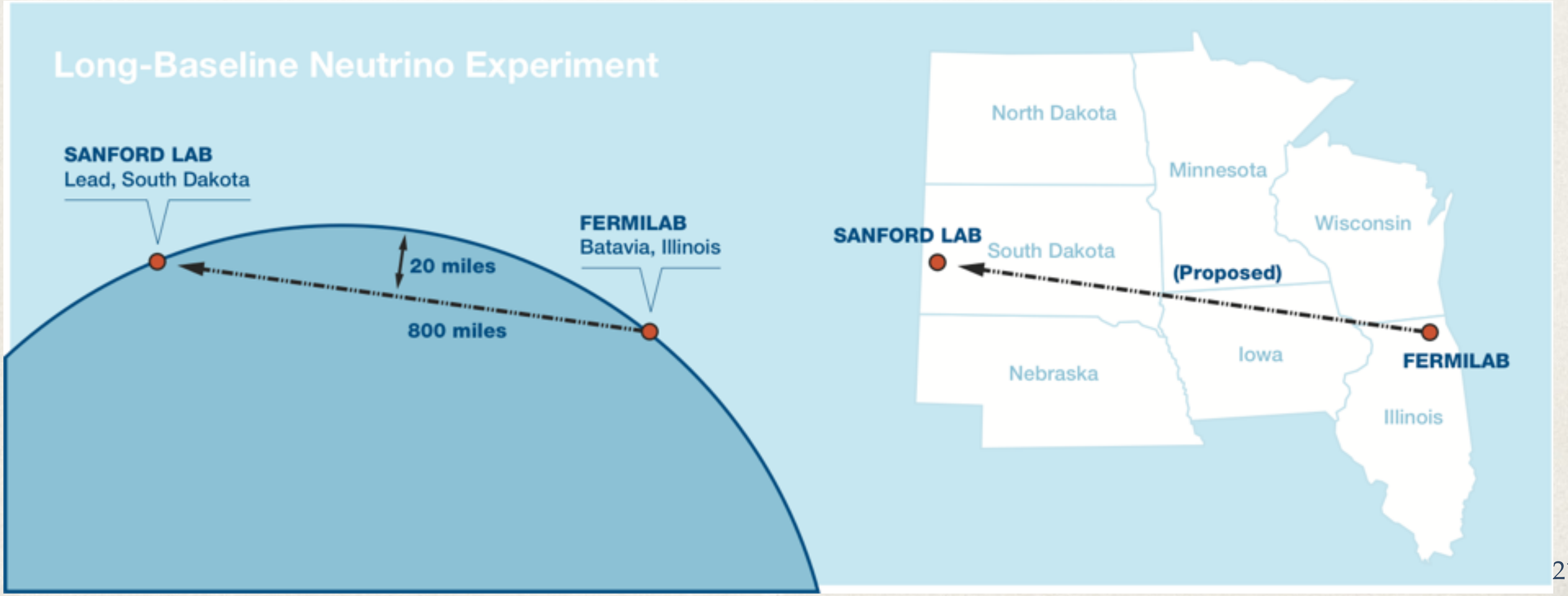
Why We Care About Cross Sections

- Here at Fermilab, we study these oscillations by studying neutrino beams of various energies after they have travelled various distances:



Why We Care About Cross Sections

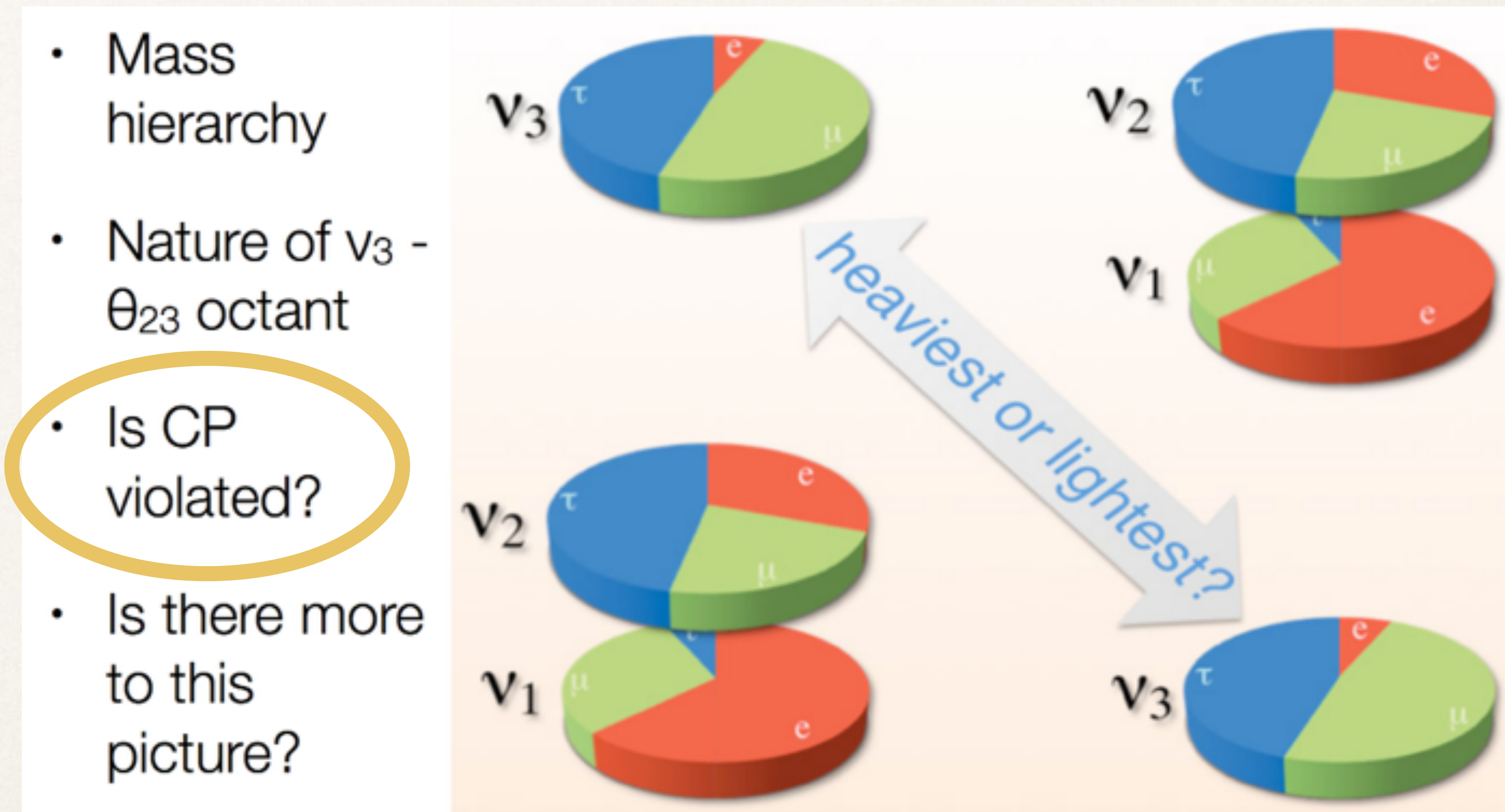
- An example — LBNE: The Long-Baseline Neutrino Experiment
  - Currently in development (DOE CD-1) to be the **flagship accelerator-based experiment in the United States**.
  - Neutrinos created at Fermilab will travel to a liquid Argon TPC detector in the Sanford Underground Research Facility (SURF) in South Dakota.
  - Priority measurements: **neutrino mass hierarchy and CP phase**



Why We Care About Cross Sections

- As Mark pointed out, the next big questions in neutrino physics involve studying the details of the oscillation parameters:

Let's consider one of these, CP violation, as an example



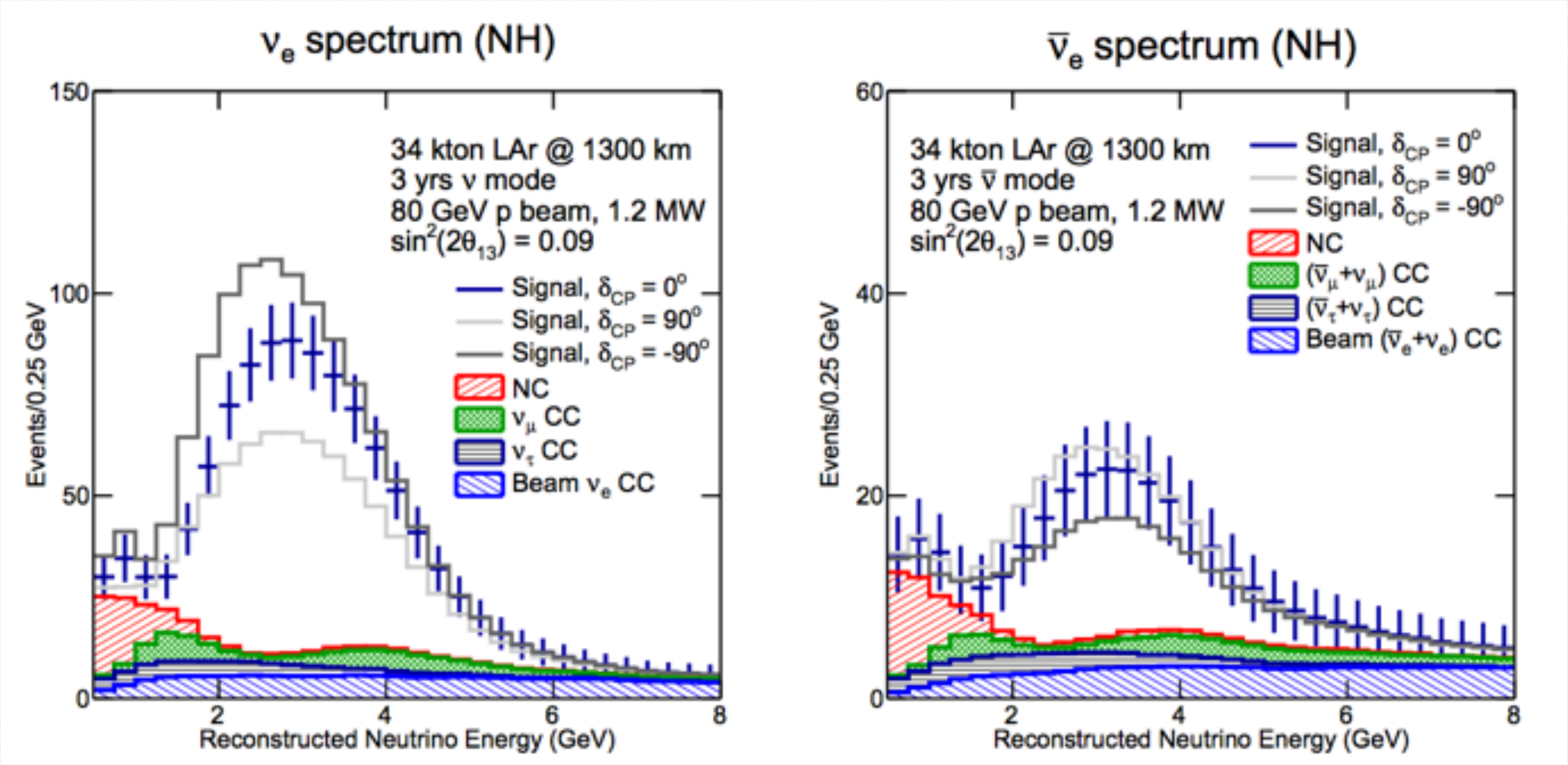
M. Messier

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Why We Care About Cross Sections

- The CP violating phase can be probed by studying $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations:

For example, LBNE will look at the energy spectra of ν_e and $\bar{\nu}_e$ appearing in primarily ν_μ and $\bar{\nu}_\mu$ beams:



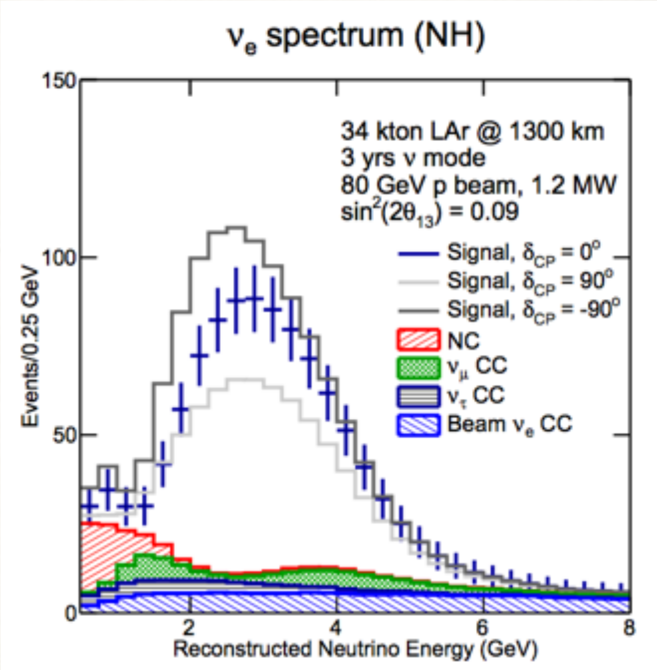
- The CP phase will be measured by comparing distributions in data to predicted distributions like these

Why We Care About Cross Sections

- These predictions are at the heart of oscillation measurements, and require A LOT of inputs:

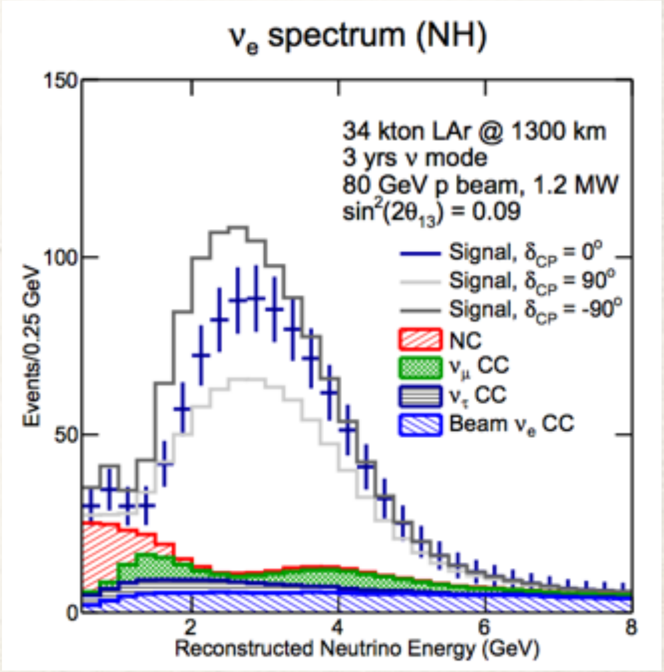
Question for the audience:

What information do we need to produce these predictions?



Why We Care About Cross Sections

- These predictions are at the heart of oscillation measurements, and require A LOT of inputs:
  - An estimate of the incoming neutrino energy spectra
  - Detailed information about neutrino interactions that occur in the neutrino detector in question
    - A list of all of the kinds of interactions that can happen
    - The probability of each type of interaction happening
    - Full kinematic information about all of the final state particles
  - A model of the detector’s response
    - Given a set of neutrino interactions, what do they actually look like in the detector?



Why We Care About Cross Sections

See talk by Z. Pavlovic
June 19th

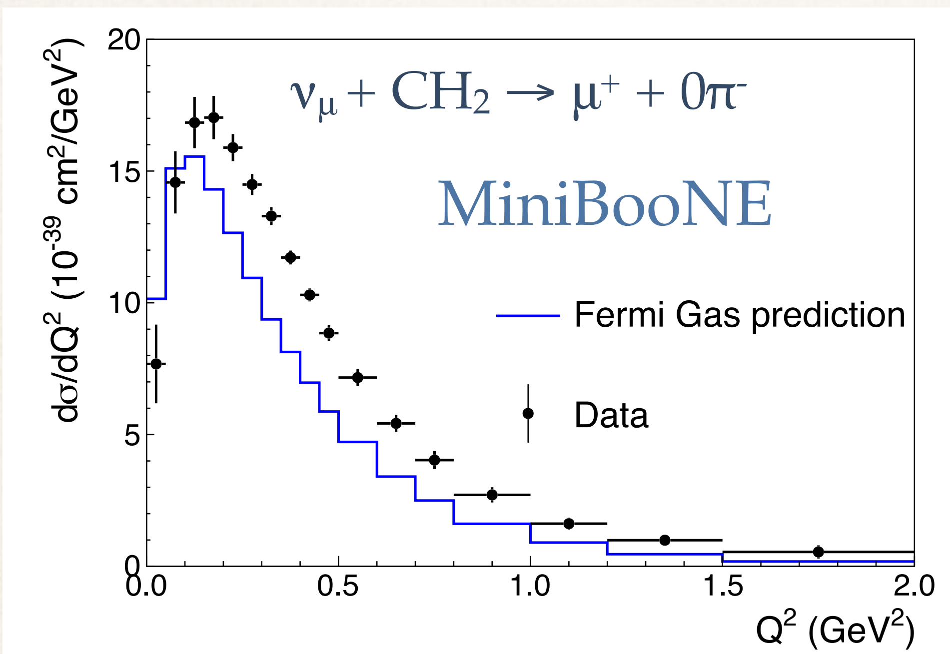
- These predictions require A LOT of inputs:
  - An estimate of the incoming neutrino spectrum
  - **A model of neutrino interactions in the material your detector is made of**
    - **A list of all of the kinds of interactions that can happen**
    - **The probability of each type of interaction happening**
    - **Full kinematic information about all of the final state particles**

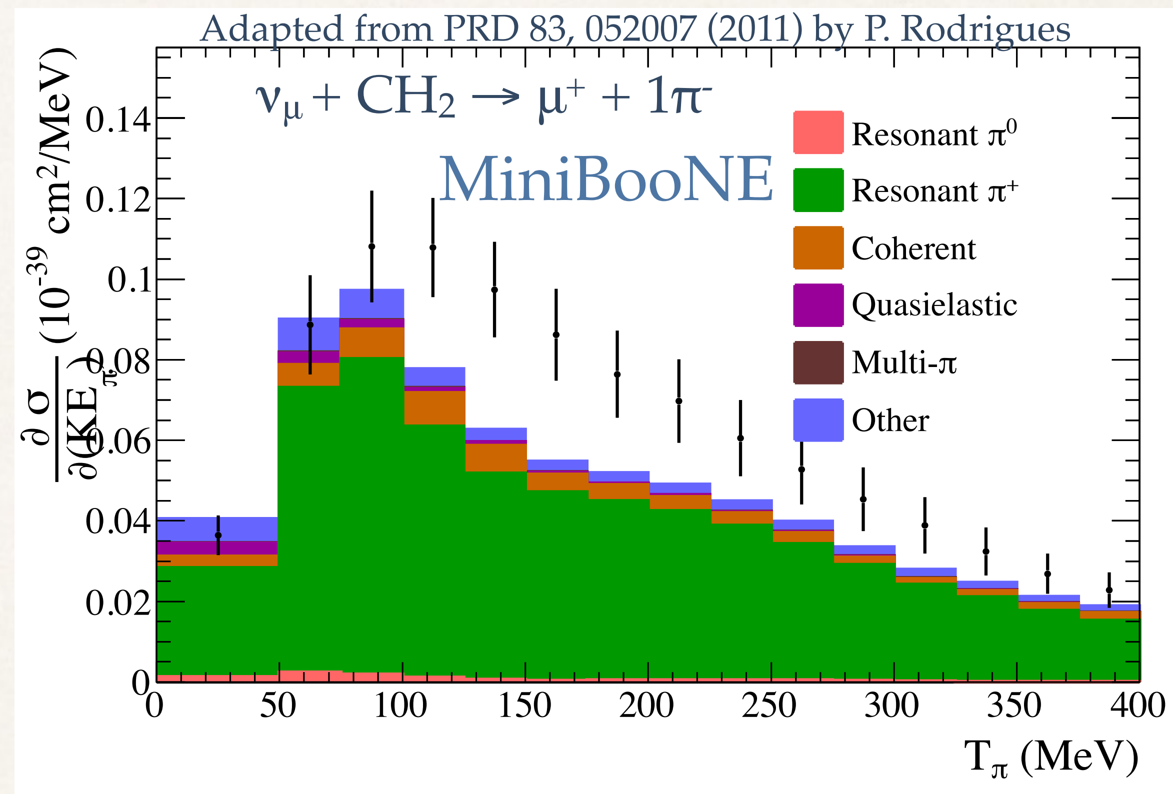
All of these things are important, but the focus of my talk today is this second point: a model of neutrino interactions

Why We Care About Cross Sections

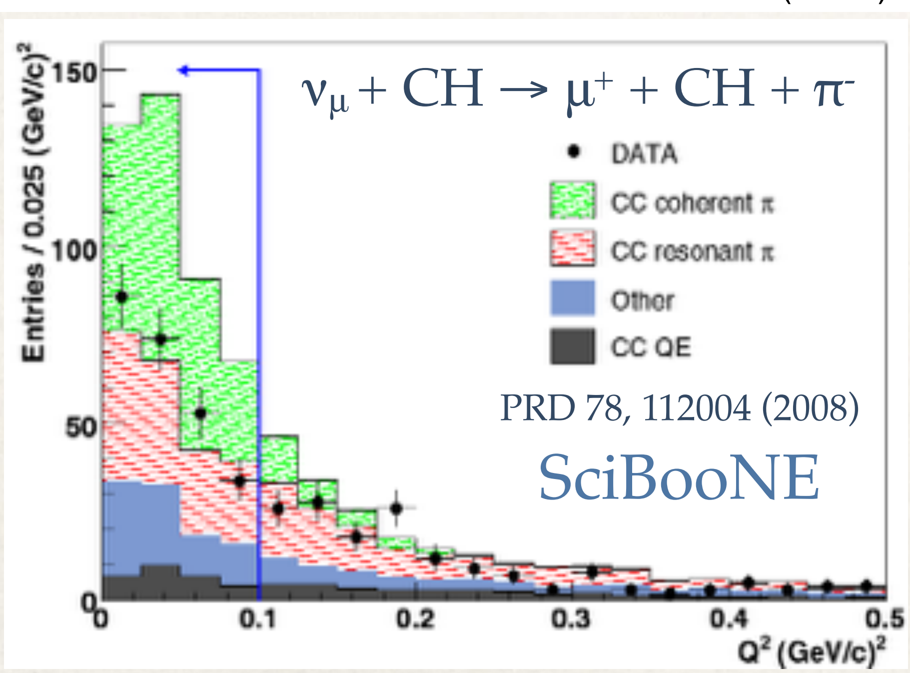
- The predictions used by modern experiments use models which do not accurately reflect cross section data:

Adapted from PRD 81, 092005 (2010) by P. Rodrigues





Adapted from PRD 83, 052007 (2011) by P. Rodrigues

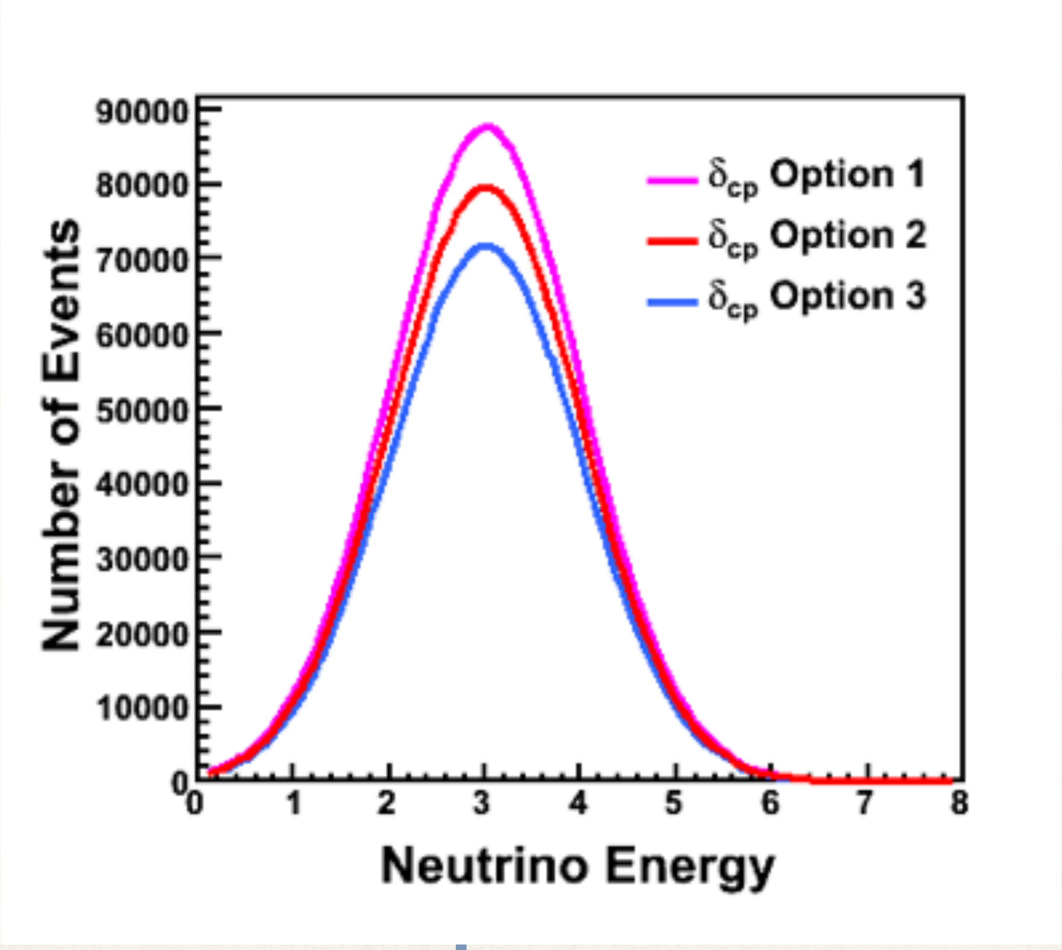


PRD 78, 112004 (2008)

- These disagreements with data lead directly to systematic uncertainties in oscillation measurements

Why We Care About Cross Sections

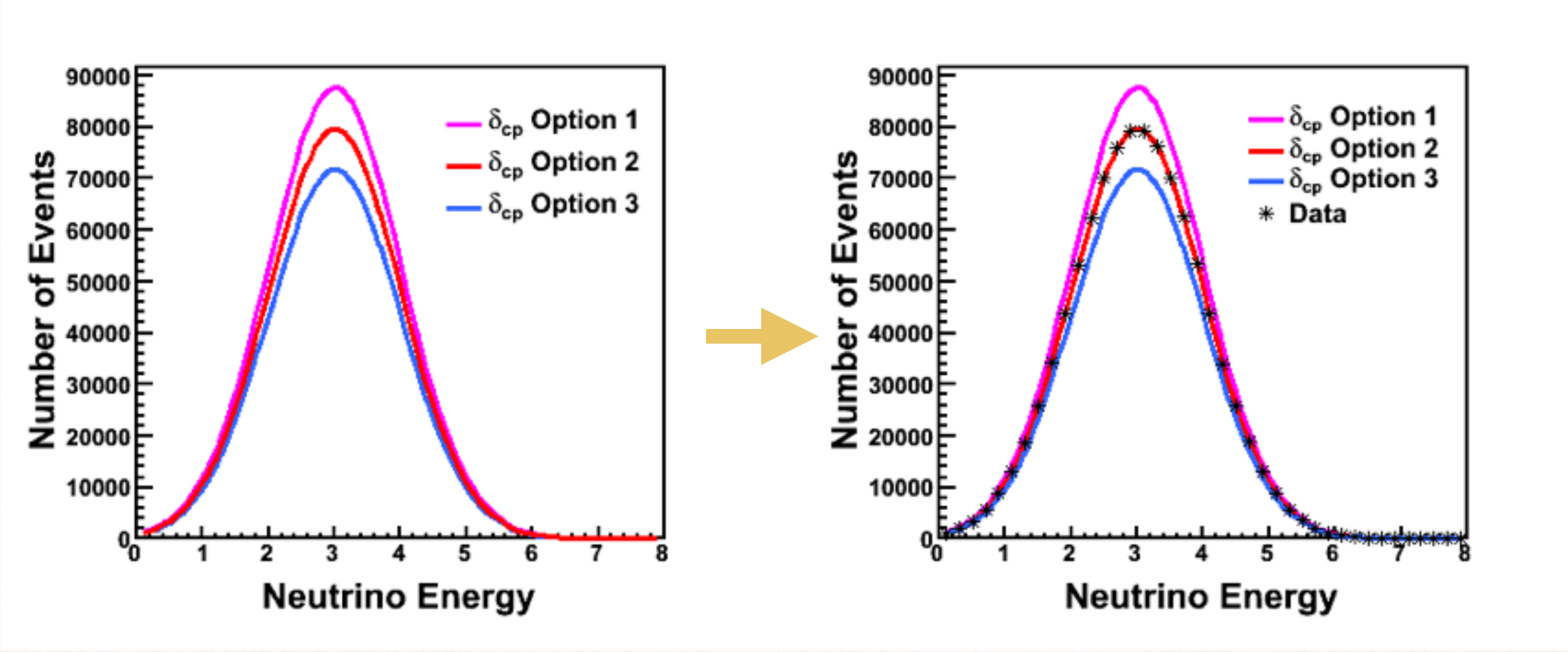
- In a perfect world, we'd have a set of predictions like this:



Just a cartoon — not real predictions!

Why We Care About Cross Sections

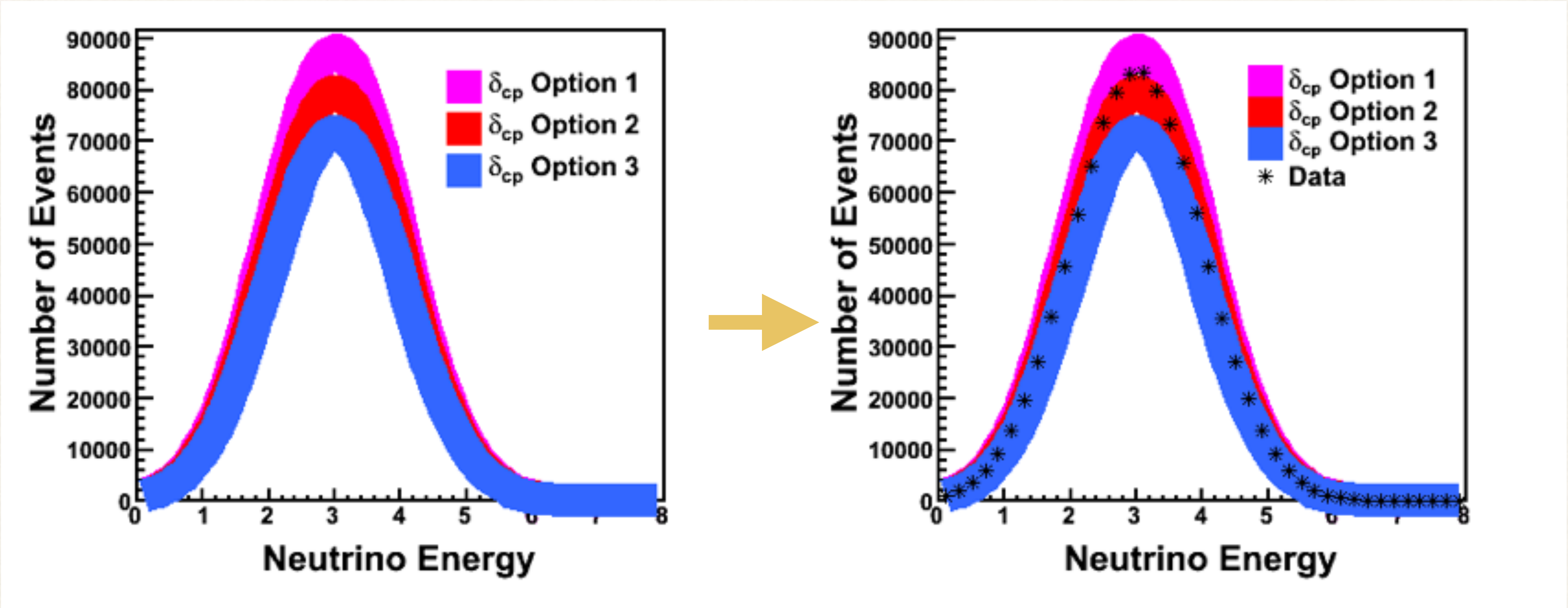
- And then we'd reconstruct put the data on top and read off the right answer:



Tada! Option 2 is the right answer!

Why We Care About Cross Sections

- But uncertainties on the neutrino interaction model muddy the picture:

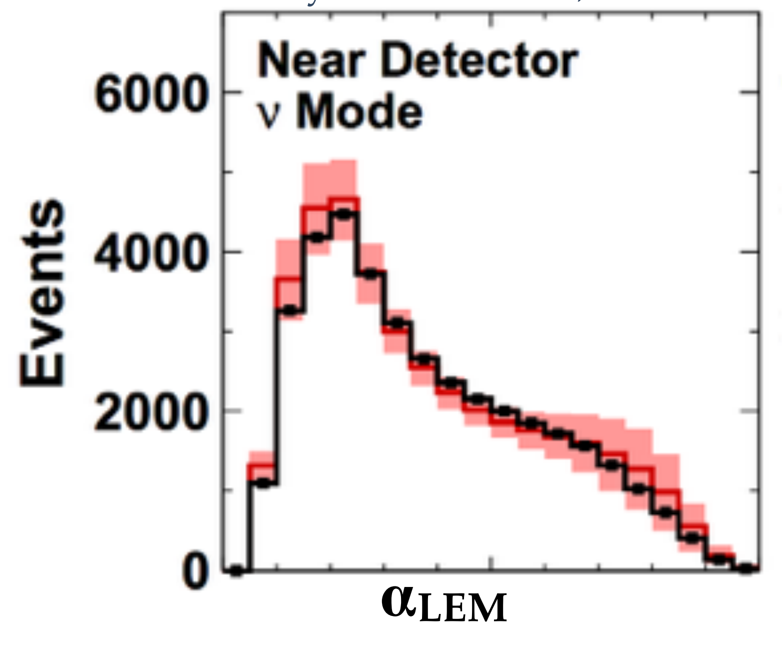


And make it more difficult to distinguish different oscillation parameters from each other

Why We Care About Cross Sections

Recent uncertainties on signal predictions
in ν_e appearance measurements:

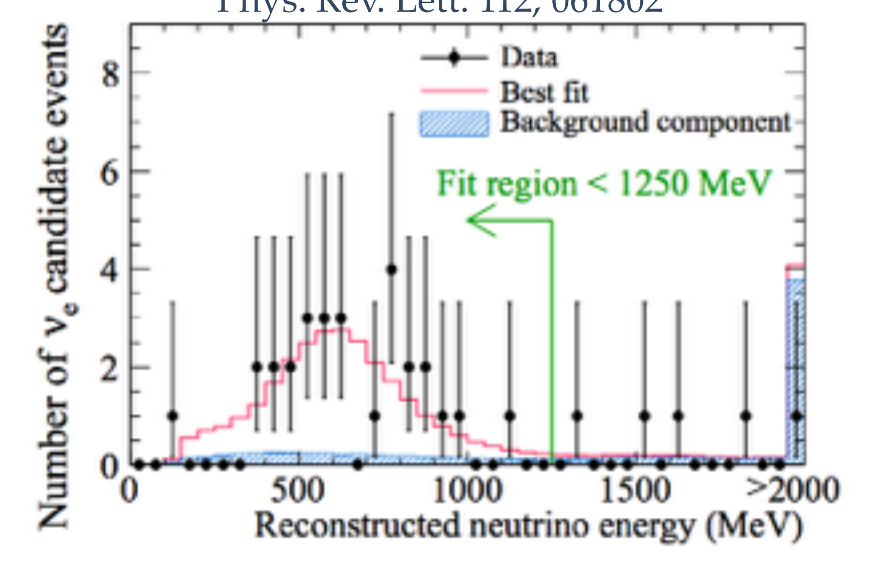
Phys. Rev. Lett. 110, 171801



MINOS uncertainty on signal prediction = 5.6%

Mix of cross section and other effects

Phys. Rev. Lett. 112, 061802



T2K (signal dominated) uncertainty on MC prediction = 8.8%

Almost all due to cross section uncertainties

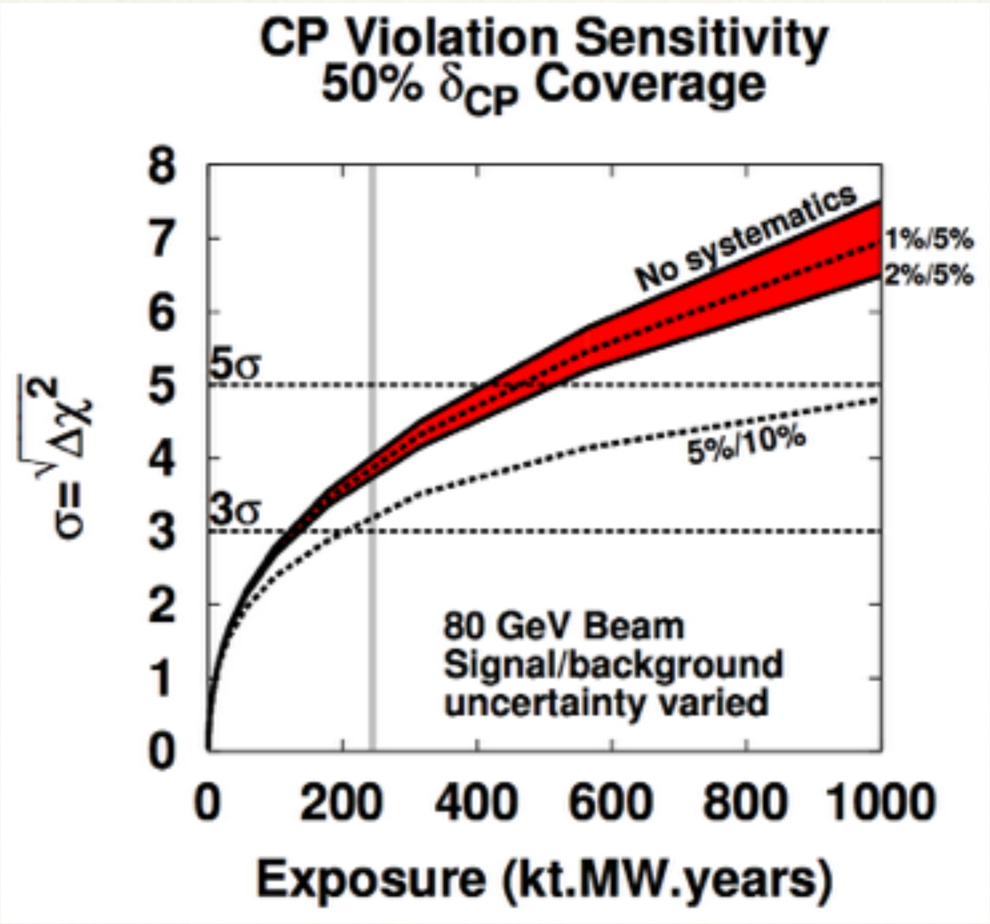
Returning to the real world, here are some examples of systematic uncertainties on the predicted number of signal events in recent oscillation measurements.

Why We Care About Cross Sections

- The impact of systematic uncertainties:

A metric for how well well be able to measure the CP phase

M. Bass NuInt 2014



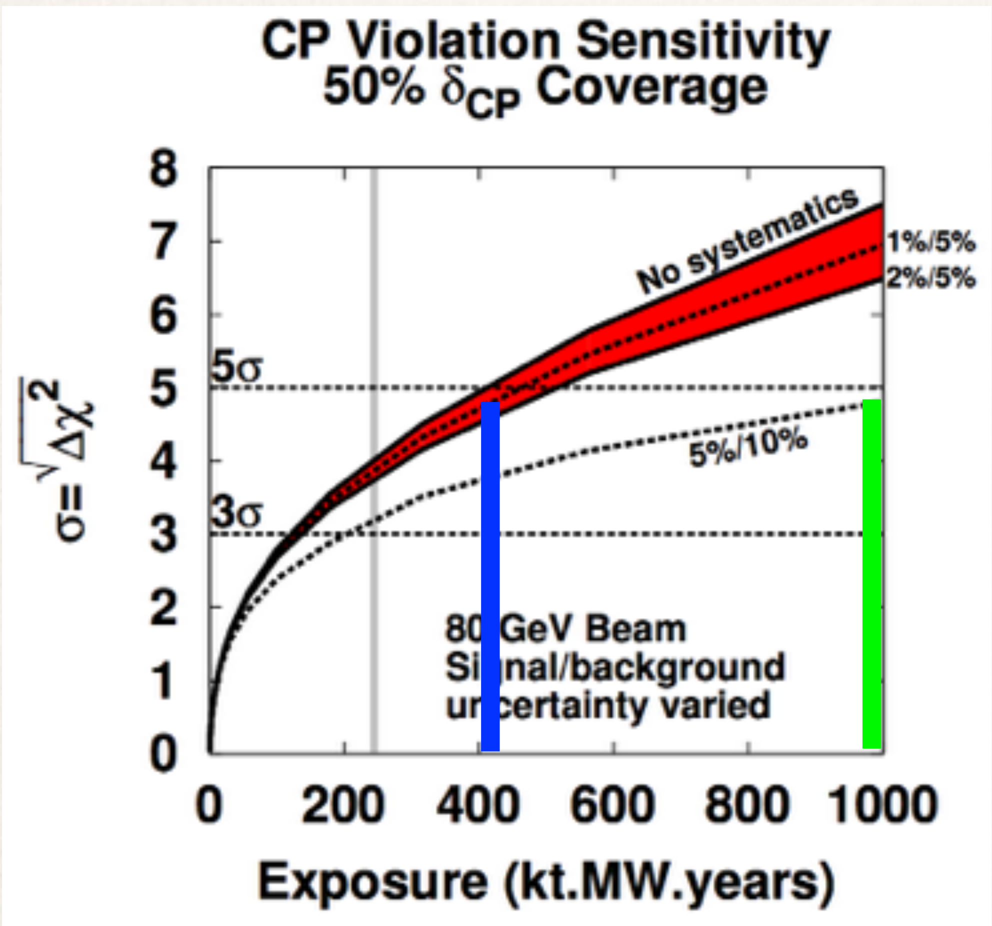
CP sensitivity versus time for several systematics scenarios

Where LBNE wants to be

Where we are now

Why We Care About Cross Sections

M. Bass NuInt 2014



10 years
x 1.2 MW
x 34 kTon

25 years
x 1.2 MW
x 34 kTon

The difference between the what we can do now and LBNE's goal is the difference between running for 10 years and 25 years

We have to understand neutrino cross sections better!

Overview of Neutrino Scattering

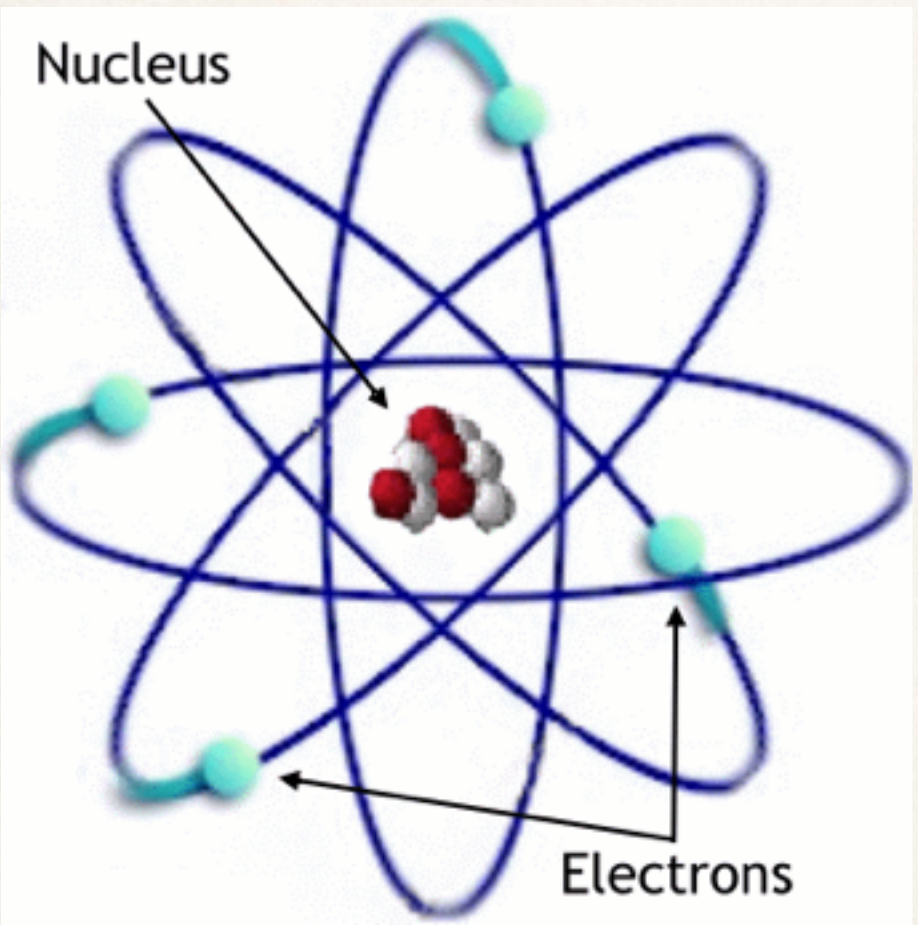
Or: what happens when a few-GeV neutrino interacts in a particle detector?

Neutrino Scattering

First a question for the audience:

When a neutrino interacts with a particle detector, what is it interacting with?

Neutrino Scattering

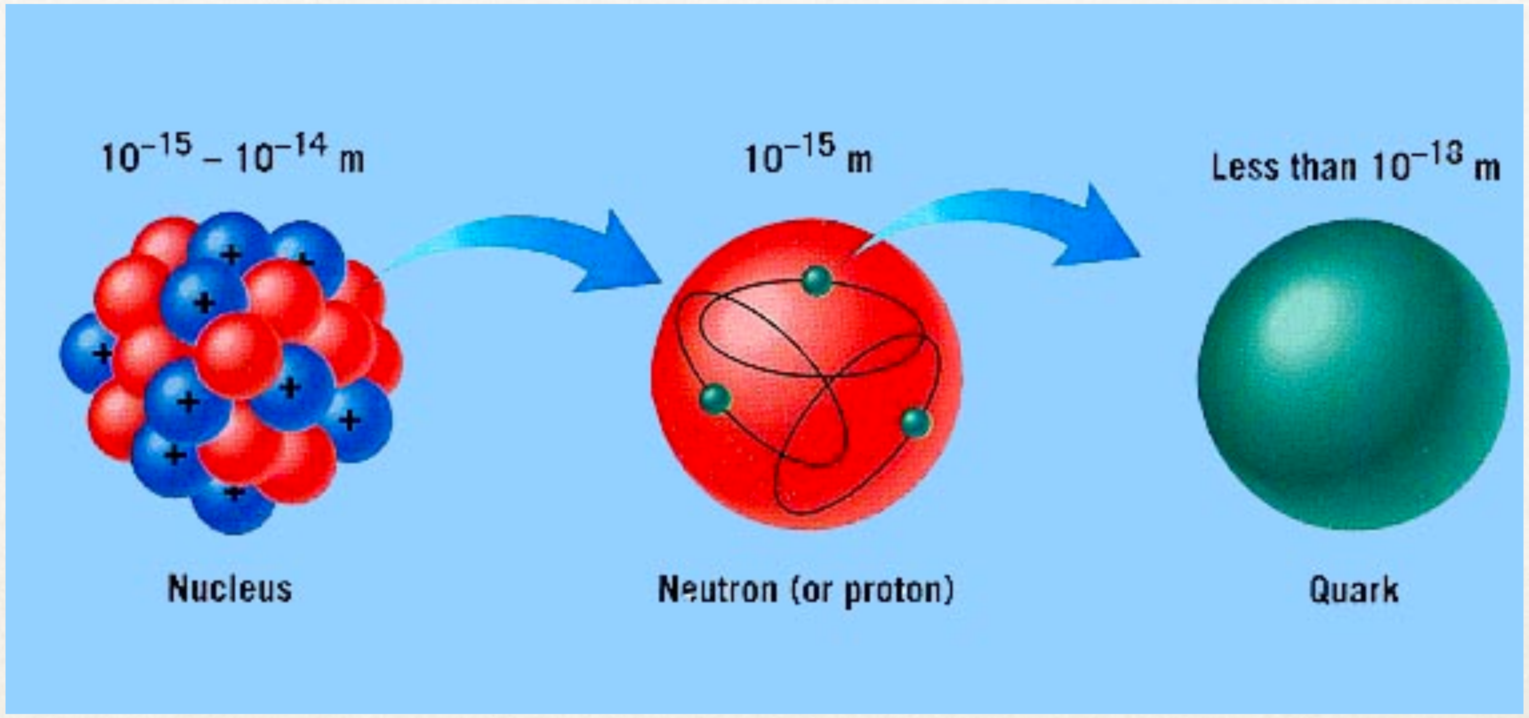


- Neutrinos can **interact with electrons or nuclei** within particle detectors
- Interaction with **a nuclei is ~2000 times more likely** than interaction with an electron
- Usually, when we talk about neutrino scattering, we mean neutrino-nucleus scattering

Neutrino Scattering

- Neutrinos can interact with a nucleus as a whole, with a nucleon (a proton or neutron) or with a quark

- This depends largely on the neutrino's energy — higher energy neutrinos access smaller length scales



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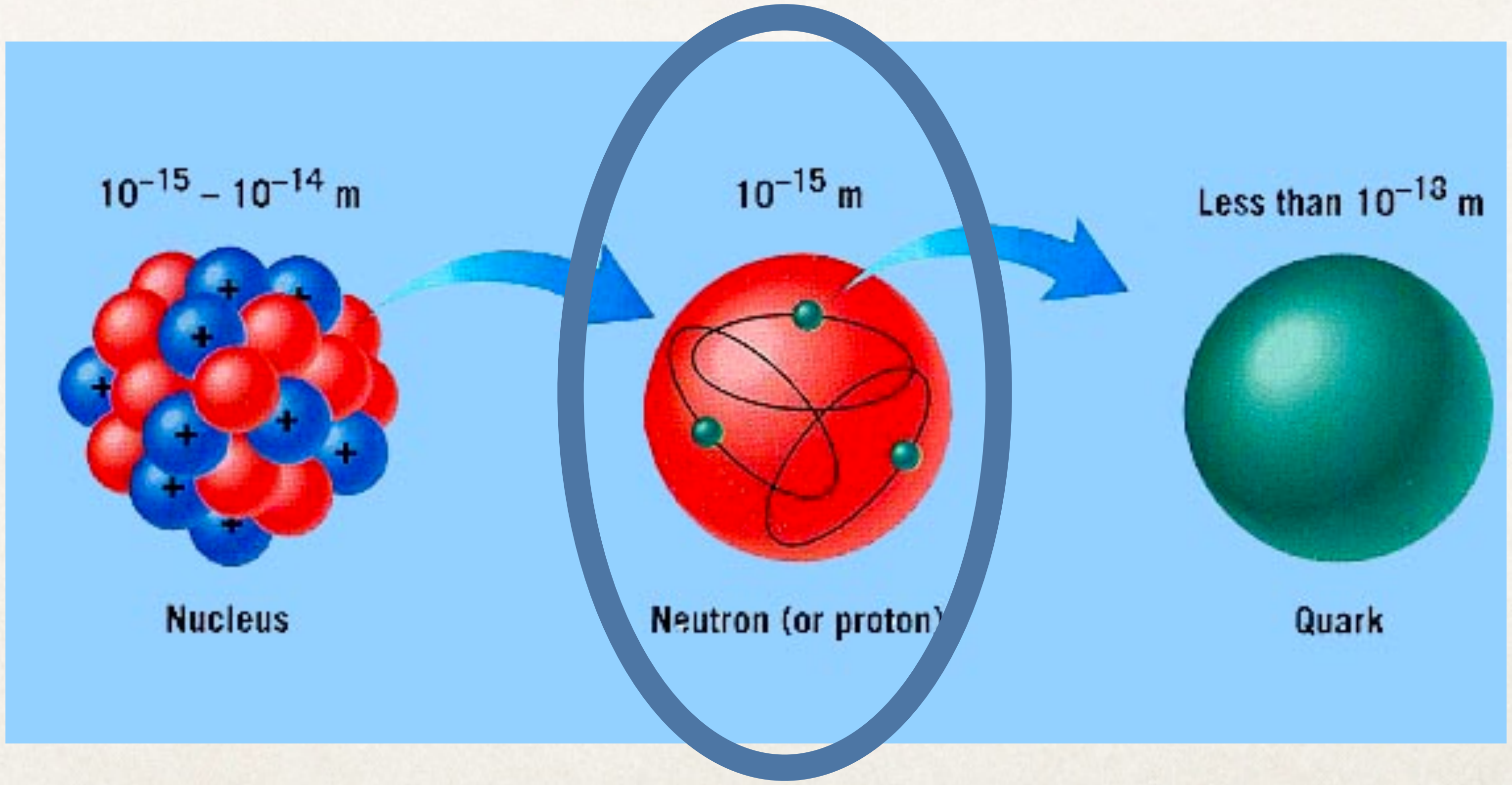


Dominant in accelrator-based oscillation measurements

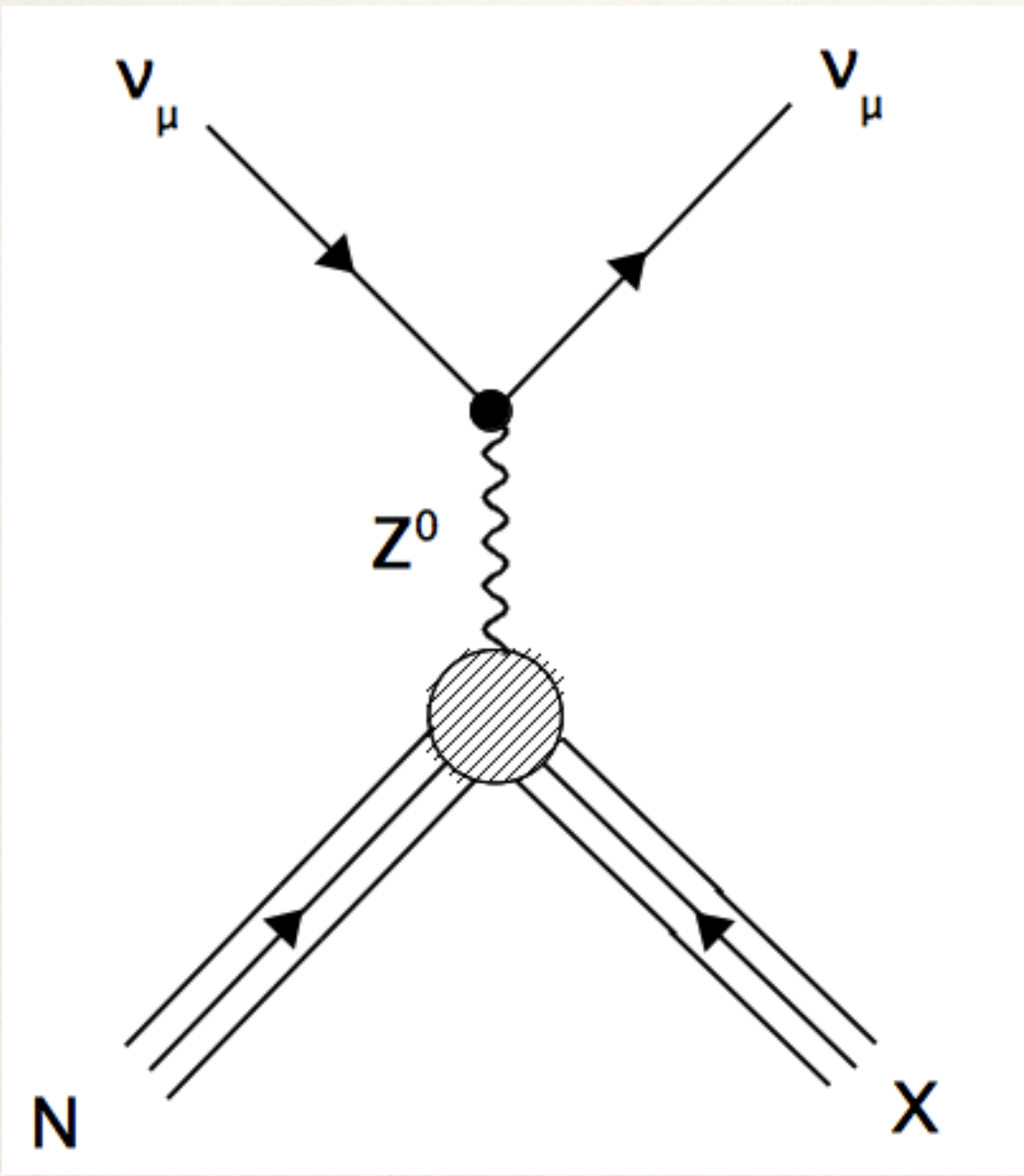
Neutrino Scattering

And another caveat…

particlezoo.net

- Most neutrino cross section experiments sit in **muon neutrino beams**
- Almost all cross section measurements are made of muon neutrinos
- We generally assume that **$\nu_\mu \rightarrow \nu_e$ cross sections are approximately equal**
  - This is also a significant source of **uncertainty for oscillation experiments**
- Experiments are **starting to make ν_e measurements**

Neutrino-Nucleus Scattering



Neutral Current

- Mediated by neutral boson
- Neutrino in initial and final state
  - Difficult to reconstruct kinematics → typically appear in oscillation measurements as backgrounds
  - Examples:

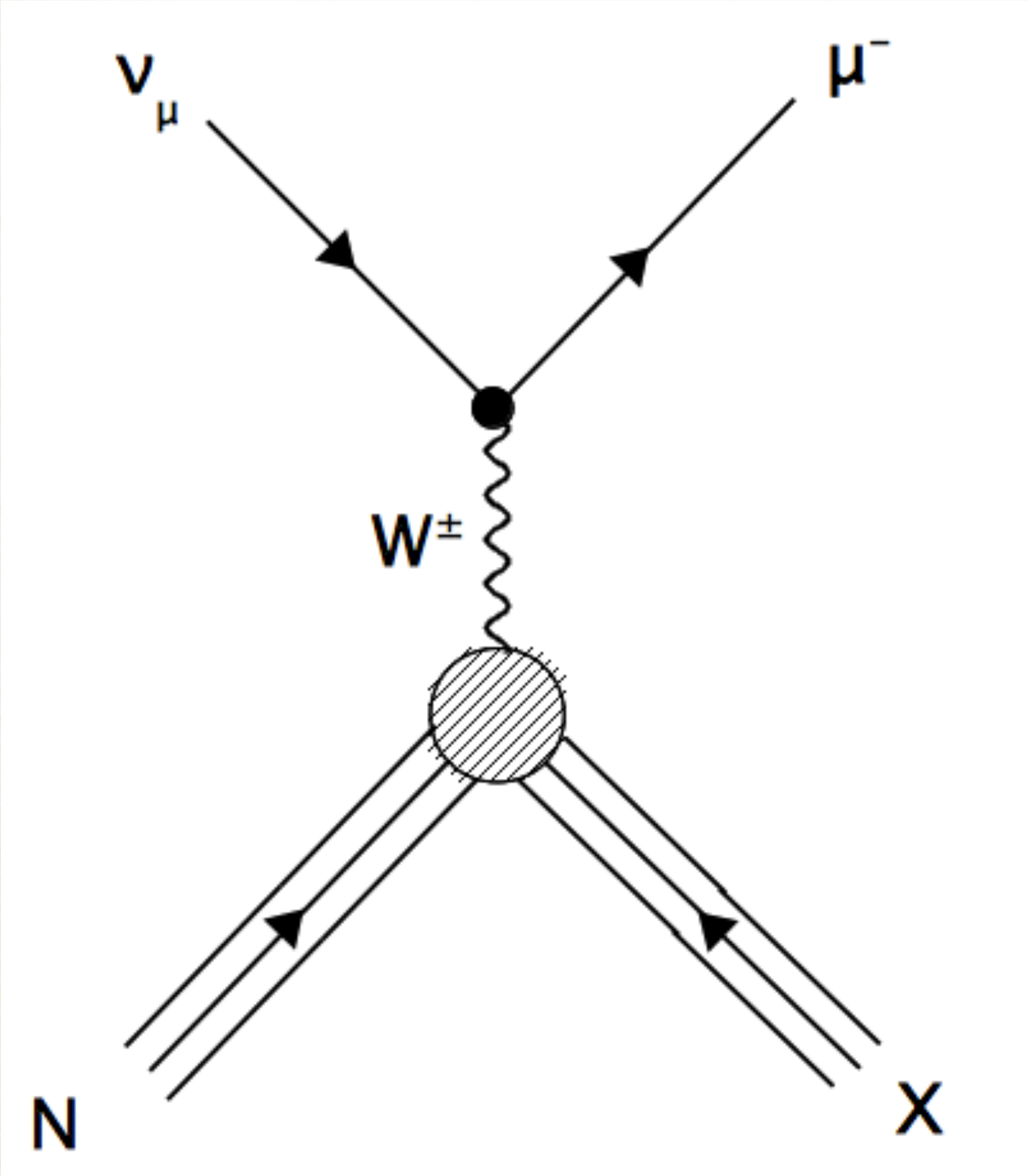
NC Elastic:

$\nu\, p \rightarrow \nu\, p$

NC π^0 production:

$\nu\, p \rightarrow \nu\, p\, \pi^0$

Neutrino-Nucleus Scattering



Charged Current

- Mediated by charged boson
- Charged lepton in final state
  - Easier kinematic reconstruction → typically used as signal channels in oscillation experiments
  - Examples:

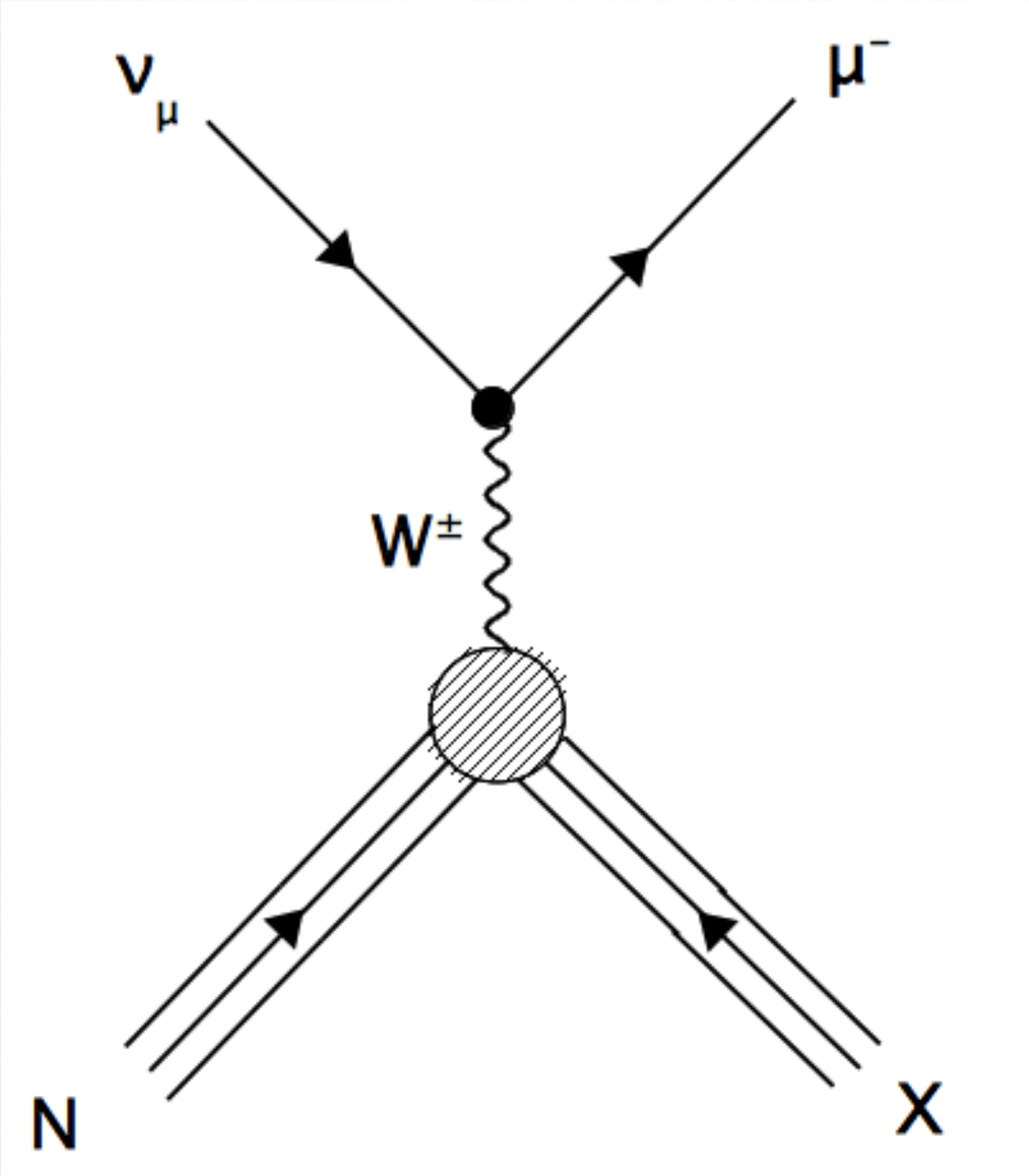
Quasi-Elastic:

$\nu\, n \rightarrow l\, p$

Pion Production:

$\nu\, p \rightarrow l\, p\, \pi$

Neutrino-Nucleus Scattering



Charged Current

- Mediated by charged boson
- Charged lepton in final state
  - Easier kinematic reconstruction → typically used as signal channels in oscillation experiments
  - Examples:

These are what we really, really have to understand for LBNE

Quasi-Elastic:

$\nu\, n \rightarrow l\, p$

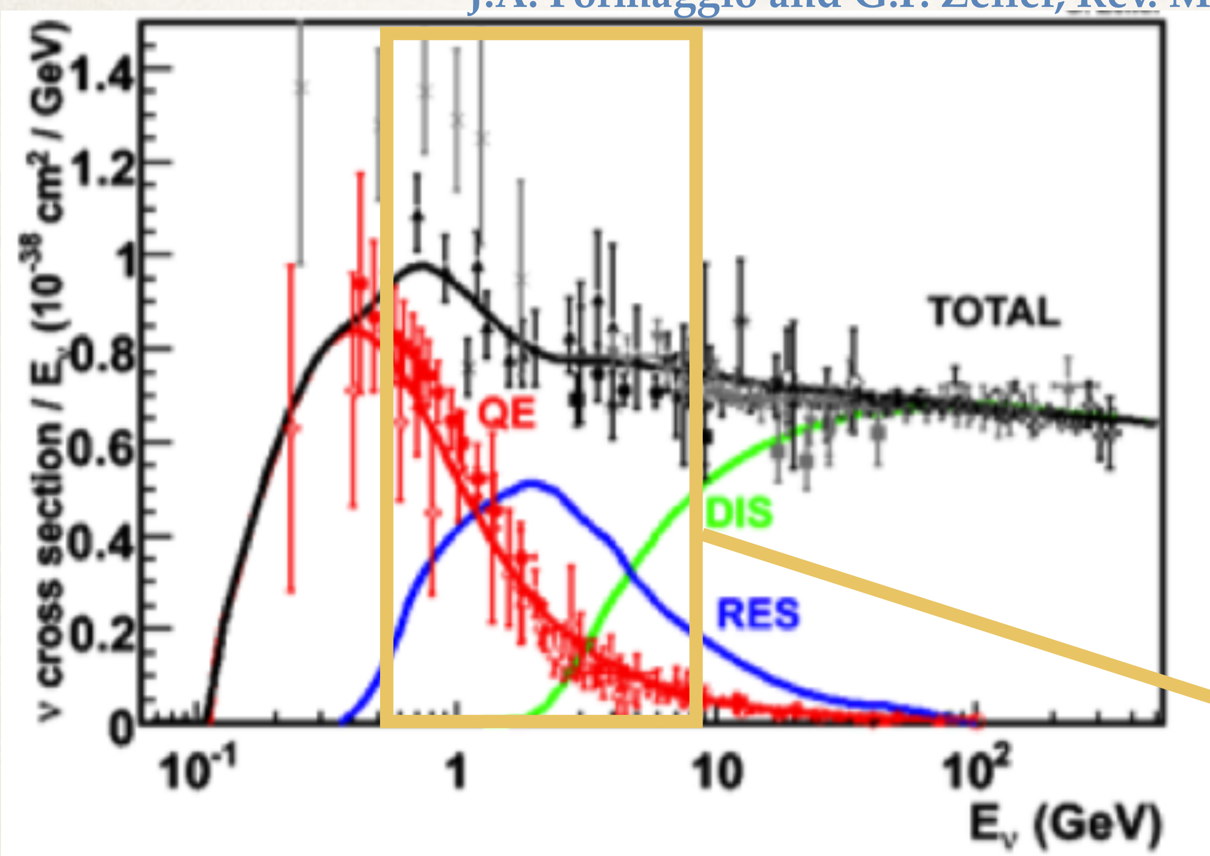
Pion Production:

$\nu\, p \rightarrow l\, p\, \pi$

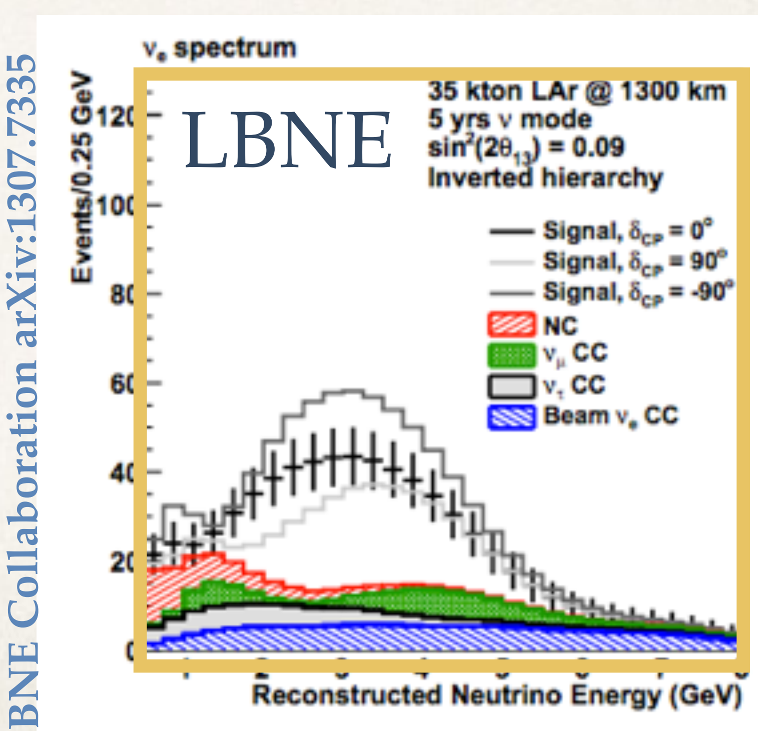
Neutrino-Nucleus Scattering

Charged current ν cross sections:

J.A. Formaggio and G.P. Zeller, Rev. Mod. Phys. 84 (2012)



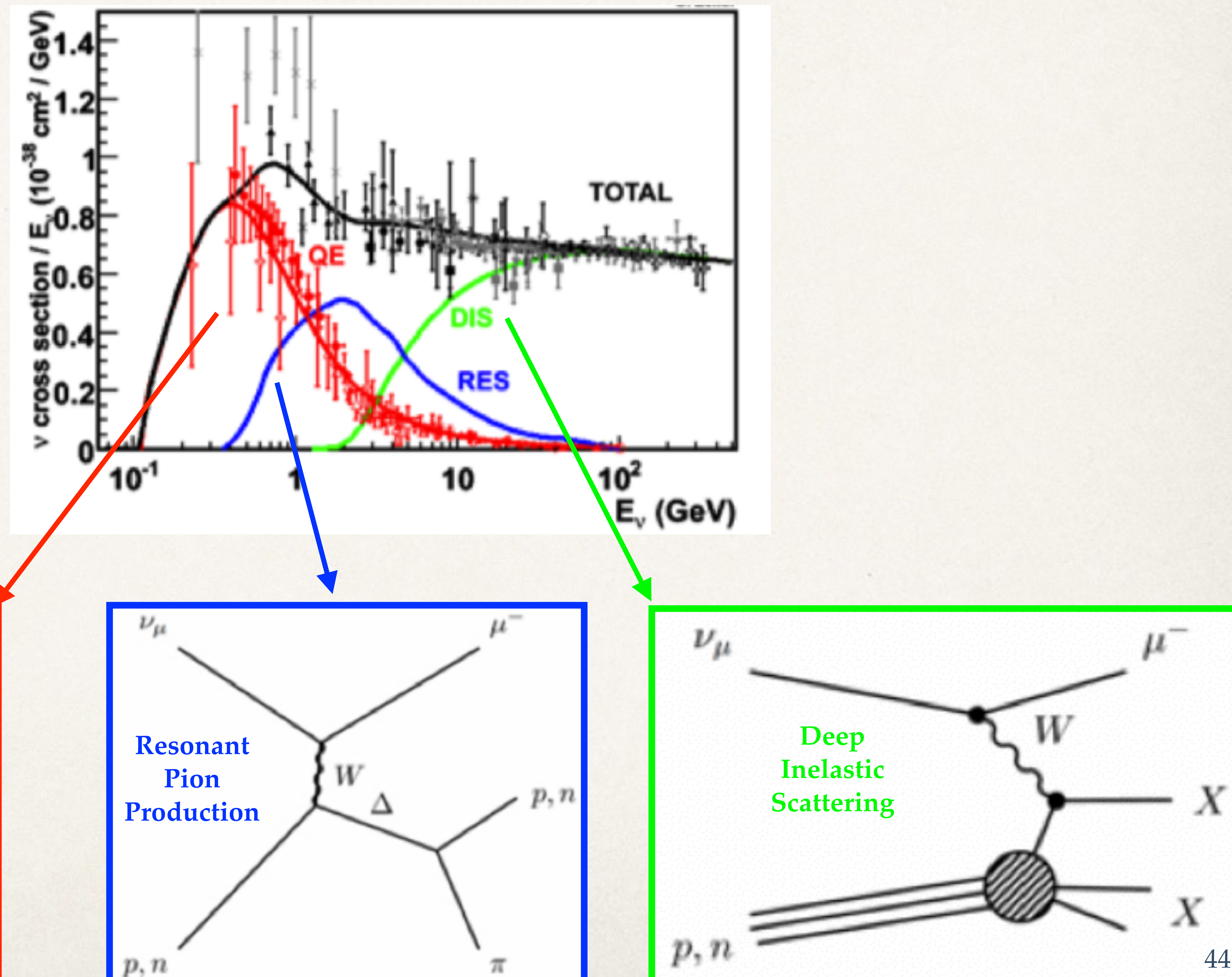
The dominant **interaction channel changes dramatically** over the region of interest to oscillation experiments



LBNE Collaboration arXiv:1307.7335

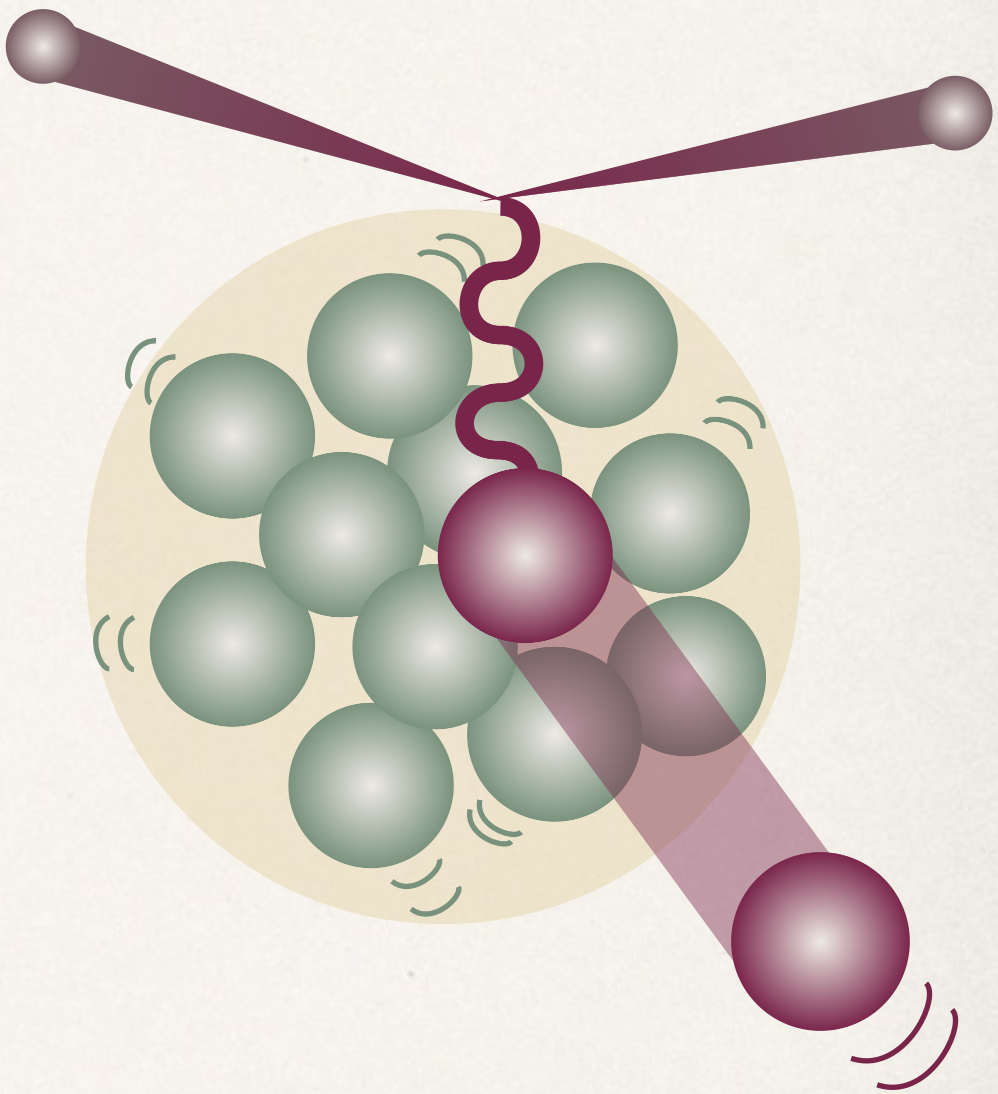
Neutrino-Nucleus Scattering

J.A. Formaggio and G.P. Zeller, Rev. Mod. Phys. 84 (2012)



Nuclear Effects

- Modern neutrino detectors are made of heavy nuclei
- The effects of the nuclear environment on neutrino interactions are substantial:
  - **Pauli blocking** of final state nucleons reduces cross sections and sculpts kinematic distributions
  - **Hadrons frequently interact** before exiting nucleus → changes number and spectrum of final state particles
  - Initial state nucleons have unknown momentum due to **Fermi motion** → skews reconstruction of neutrino energy
  - Neutrinos can interact with **multi-nucleon bound states**



Much of the uncertainty on cross section models is due to these poorly understood effects

Neutrino Cross Section Measurements:

The Basics

Neutrino Scattering Measurements

- A reminder of how we measure cross sections

Takes many years to estimate
Done separately for each measurement

$$\sigma = \frac{\text{Number of Interactions}}{\Phi \times N}$$

Also takes many years to estimate
Done ~once and used by many measurements

Not hard or lengthy as long as you were careful when you built your detector
(also you get to use Avogadro's number!)

Neutrino Scattering Measurements

- A reminder of how we measure cross sections

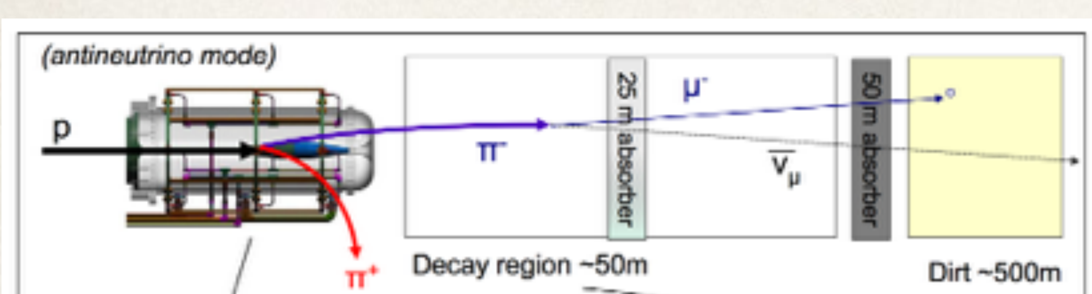
$$\sigma = \frac{\text{Number of Interactions}}{\Phi \times N}$$

Calculating flux is hard

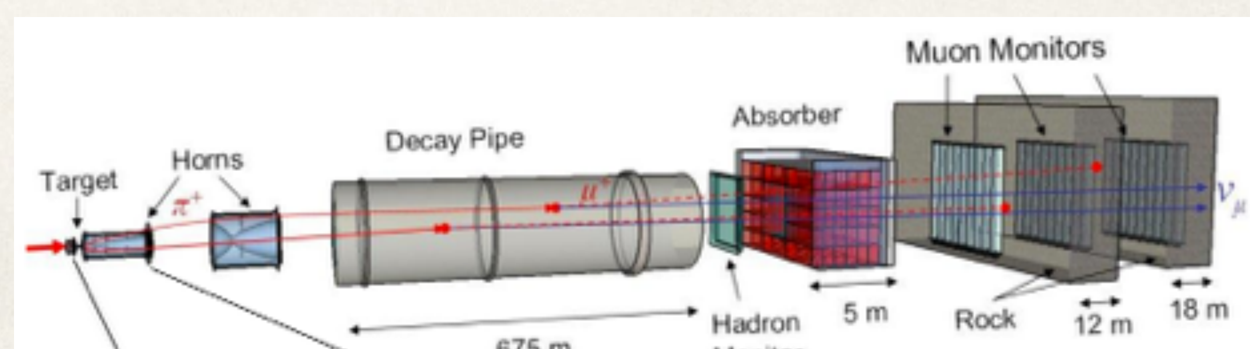
Z. Pavlović, IF Summer Lecture on June 6th

- Flux estimates are based on simulations of the neutrino beam lines, constrained with various kinds of data. Usually leading source of uncertainty on cross section measurements.

BNB



NuMI

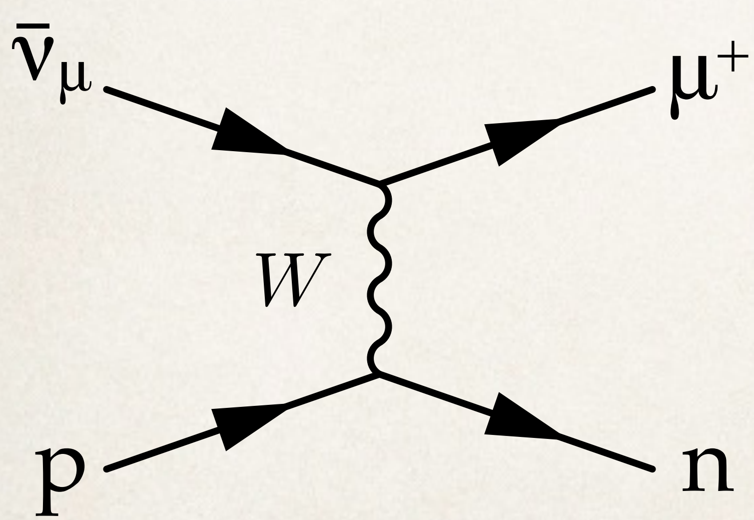


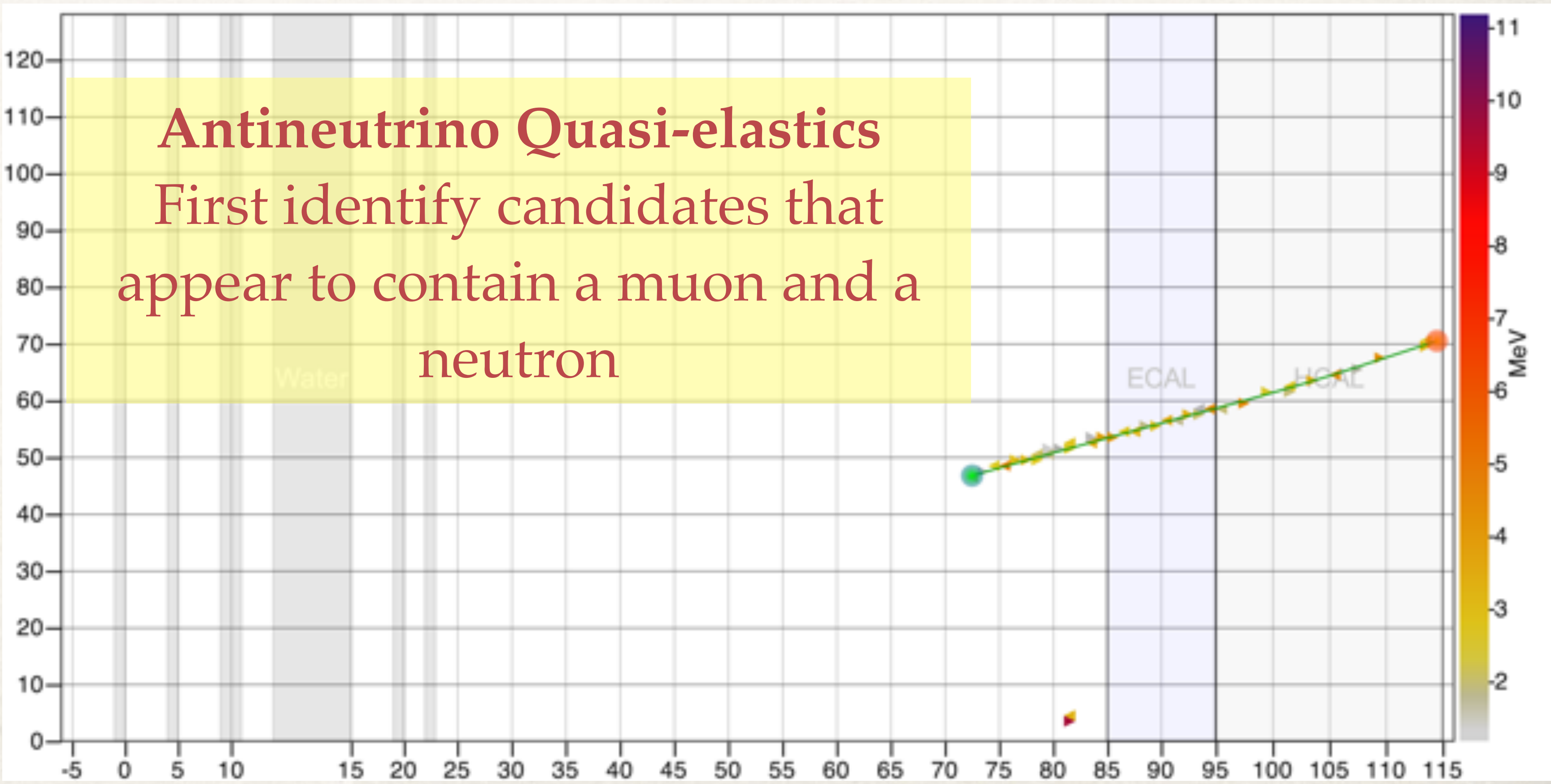
Neutrino Scattering Measurements

- A reminder of how we measure cross sections

$$\sigma = \frac{\text{Number of Interactions}}{\Phi \times N}$$

An example form MINERvA:



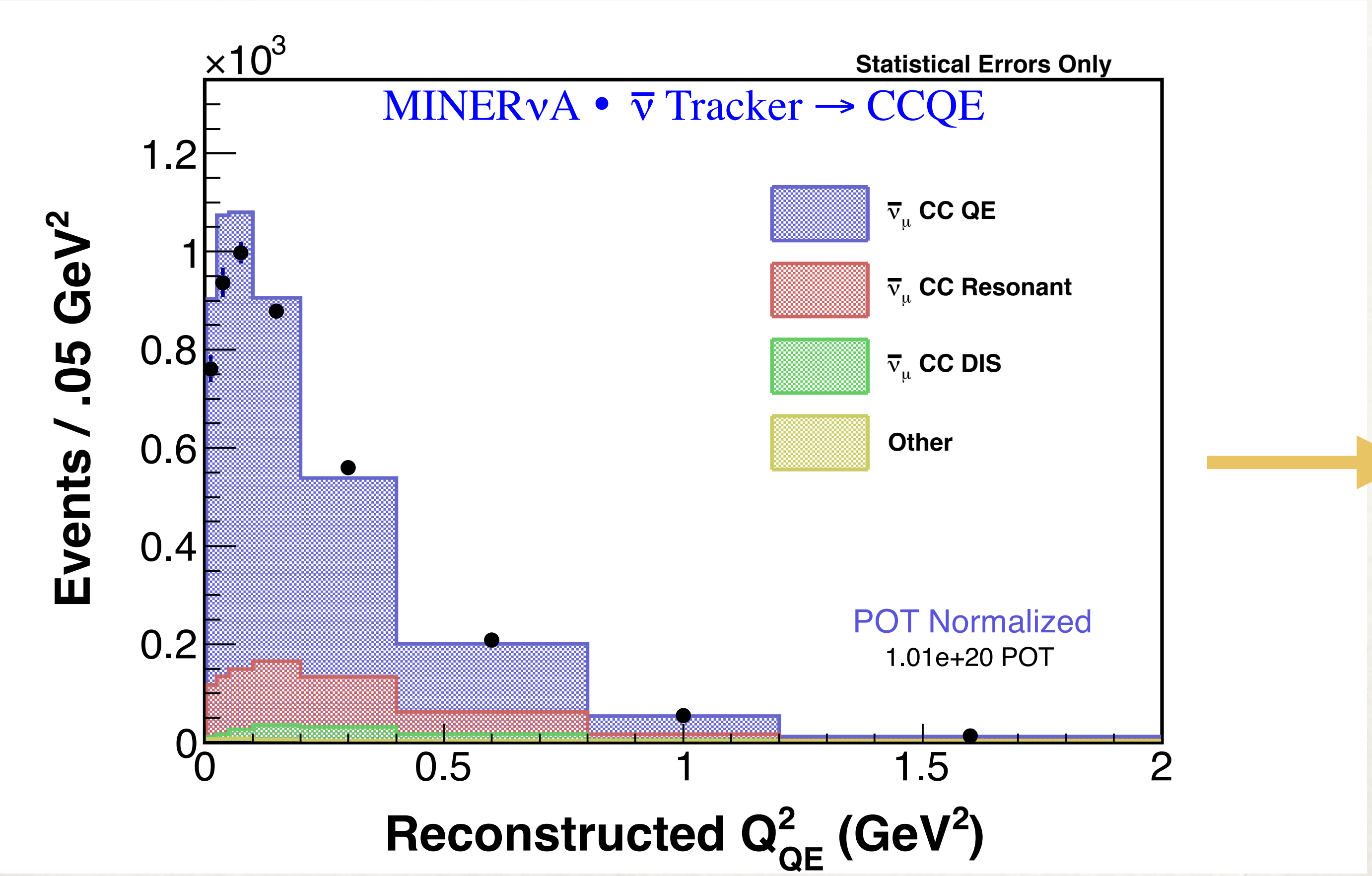


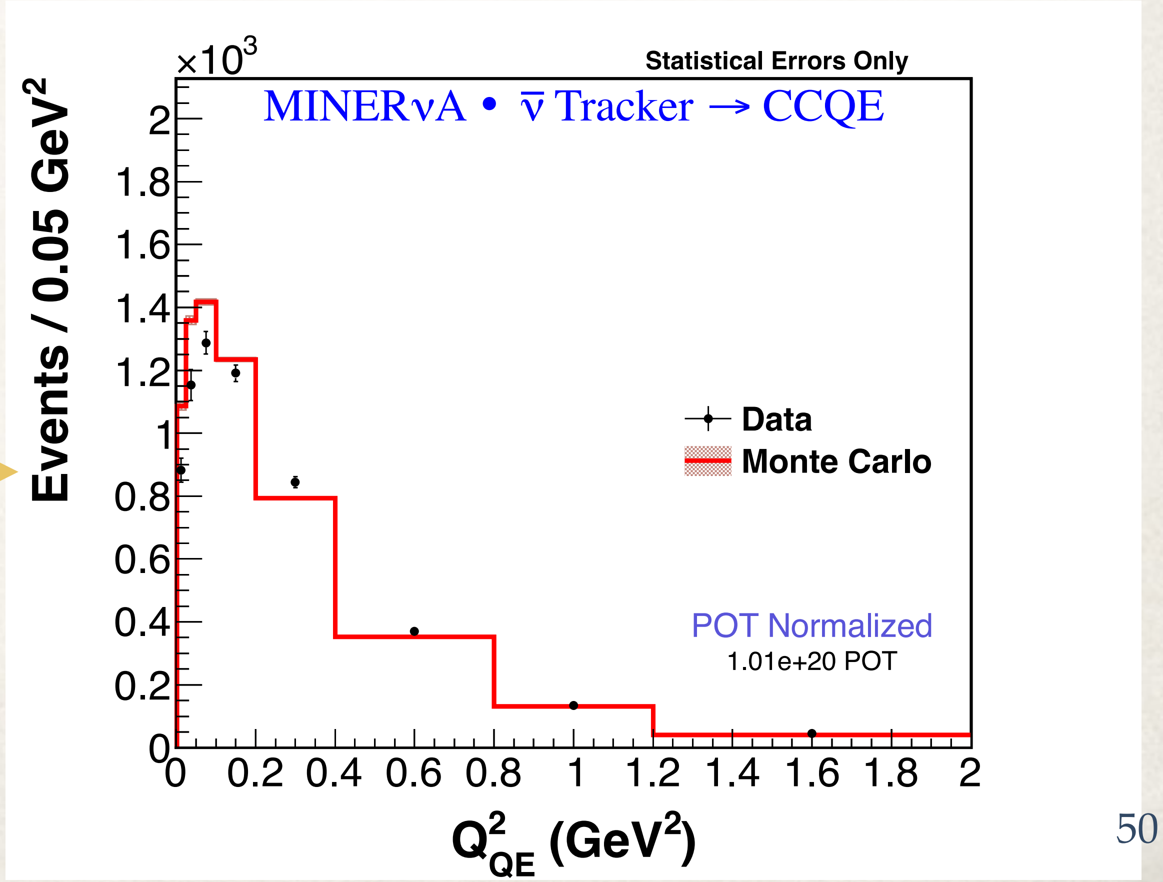
Neutrino Scattering Measurements

- A reminder of how we measure cross sections

$$\sigma = \frac{\text{Number of Interactions}}{\Phi \times N}$$

- Subtract background, correct for detector effects to estimate number of interactions:



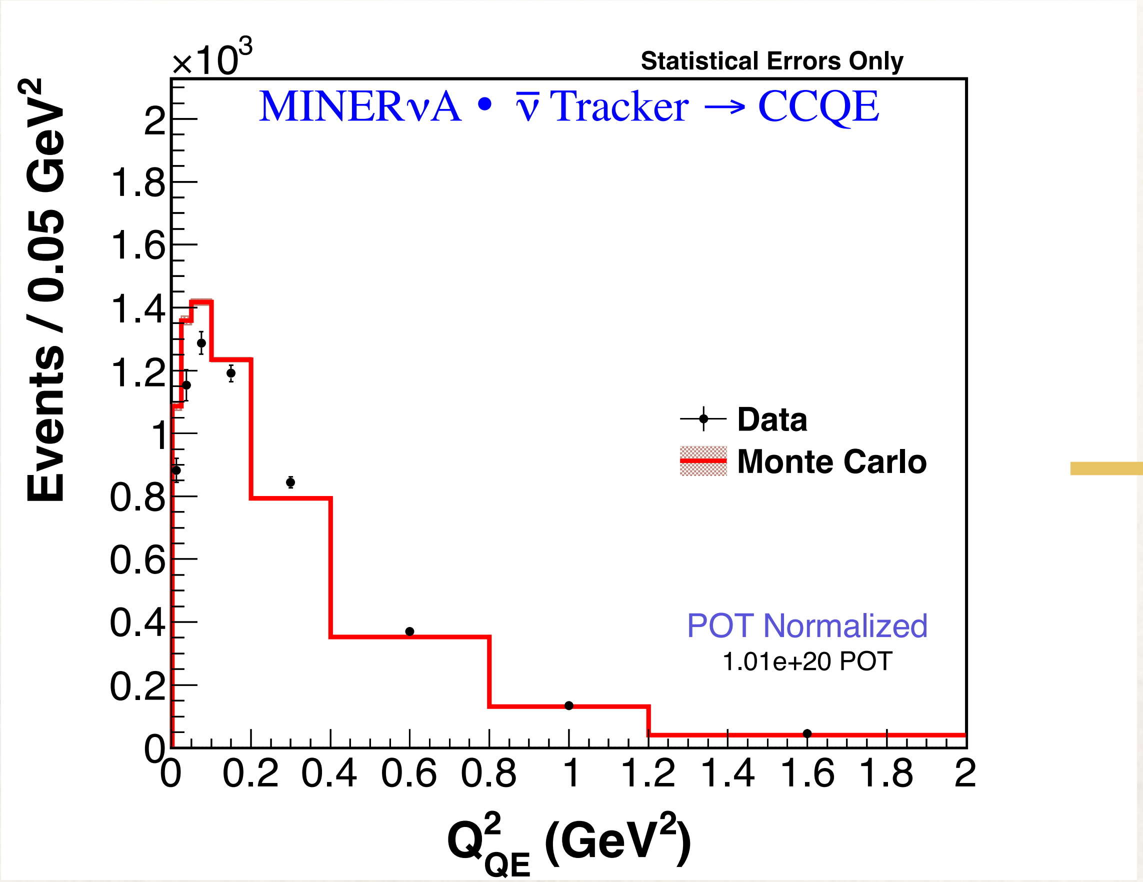


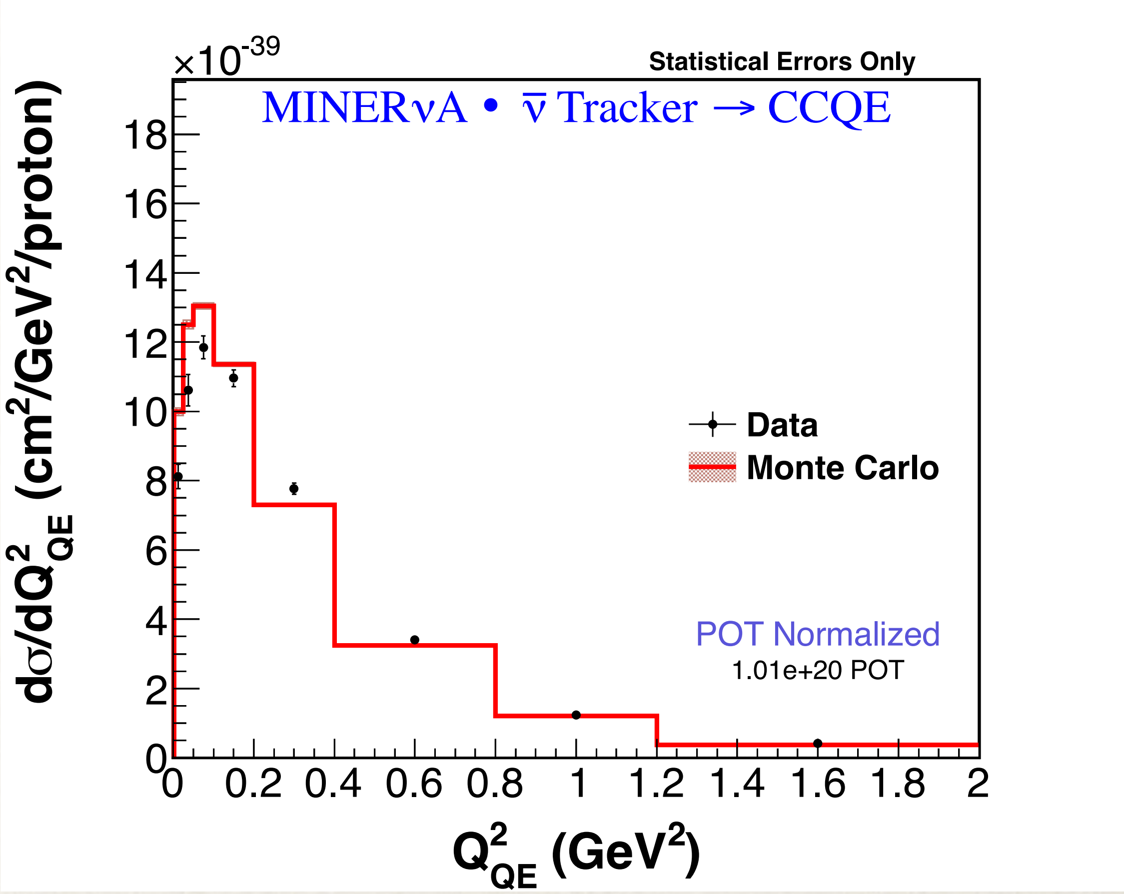
Neutrino Scattering Measurements

- A reminder of how we measure cross sections

$$\sigma = \frac{\text{Number of Interactions}}{\Phi \times N}$$

- Divide by flux and target number to get a cross section

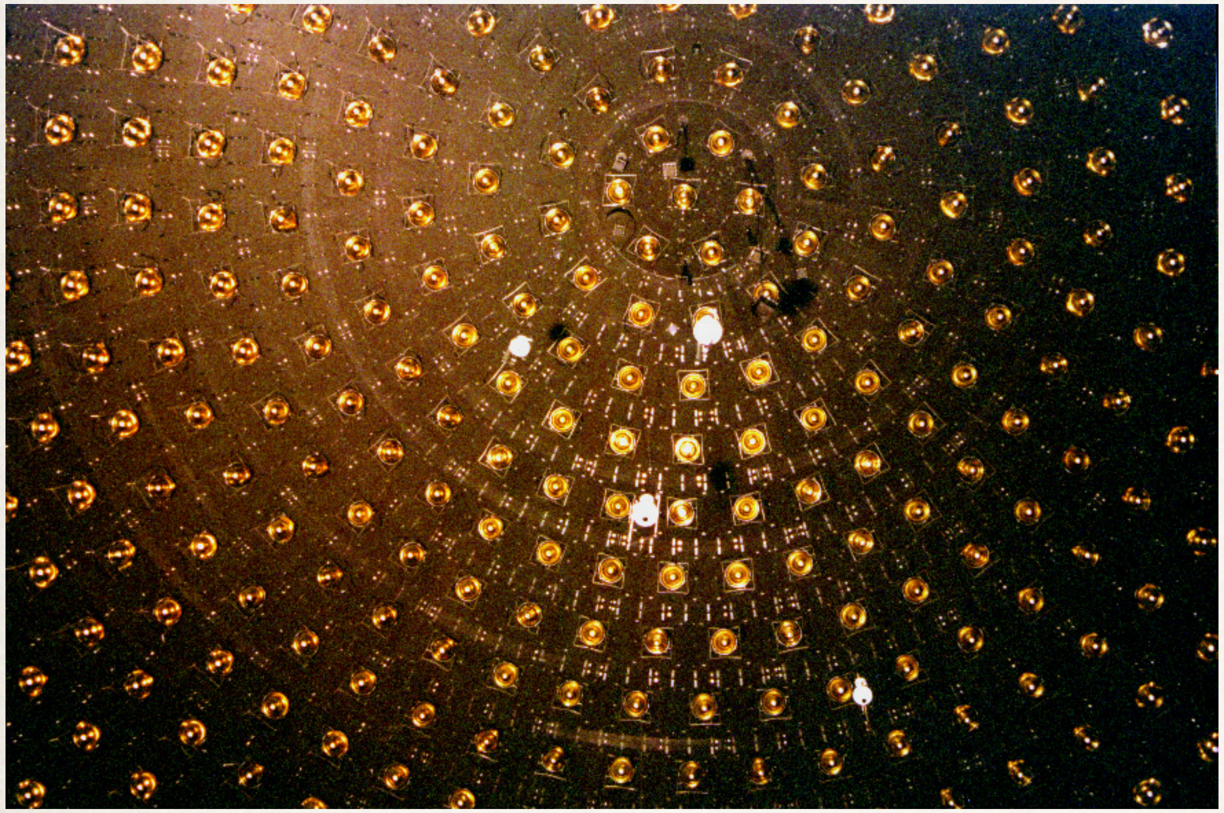




Neutrino Scattering Data:

MiniBooNE

MiniBooNE: Detector

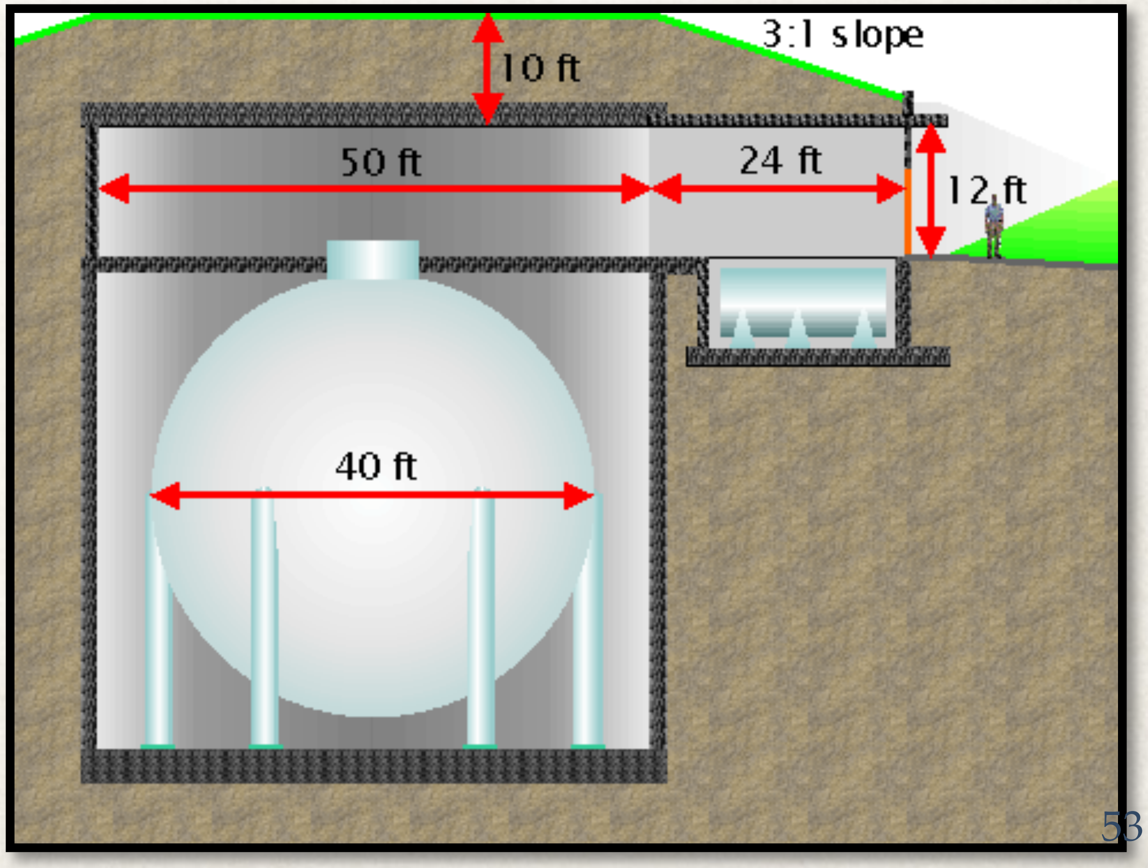


- Cherenkov detector; 12.2 m diameter sphere filled with mineral oil

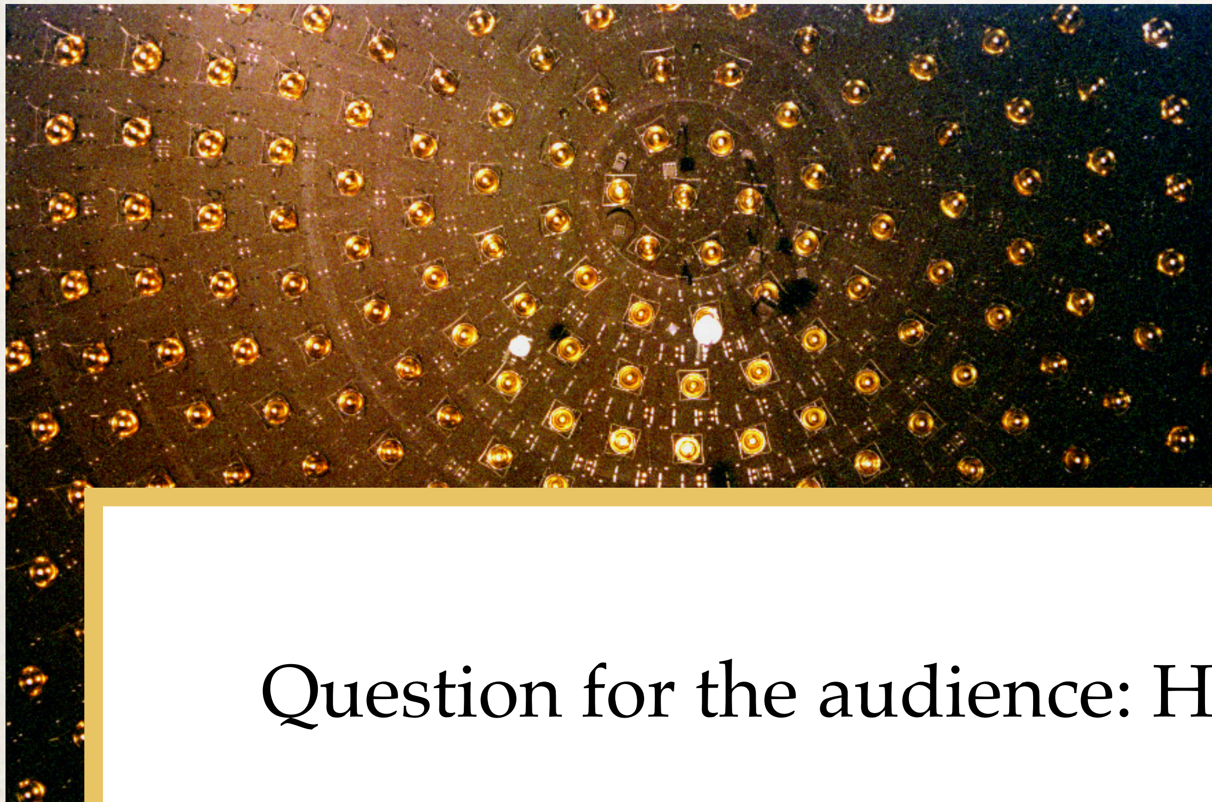
- Designed to study short-baseline ν oscillations, but also a prolific source of ν and $\bar{\nu}$ cross section measurements

- Fermilab Booster ν beam: $\langle E_\nu \rangle \sim 700$ MeV, ideally suited for studying quasi-elastic scattering

- Very large datasets and full angular coverage



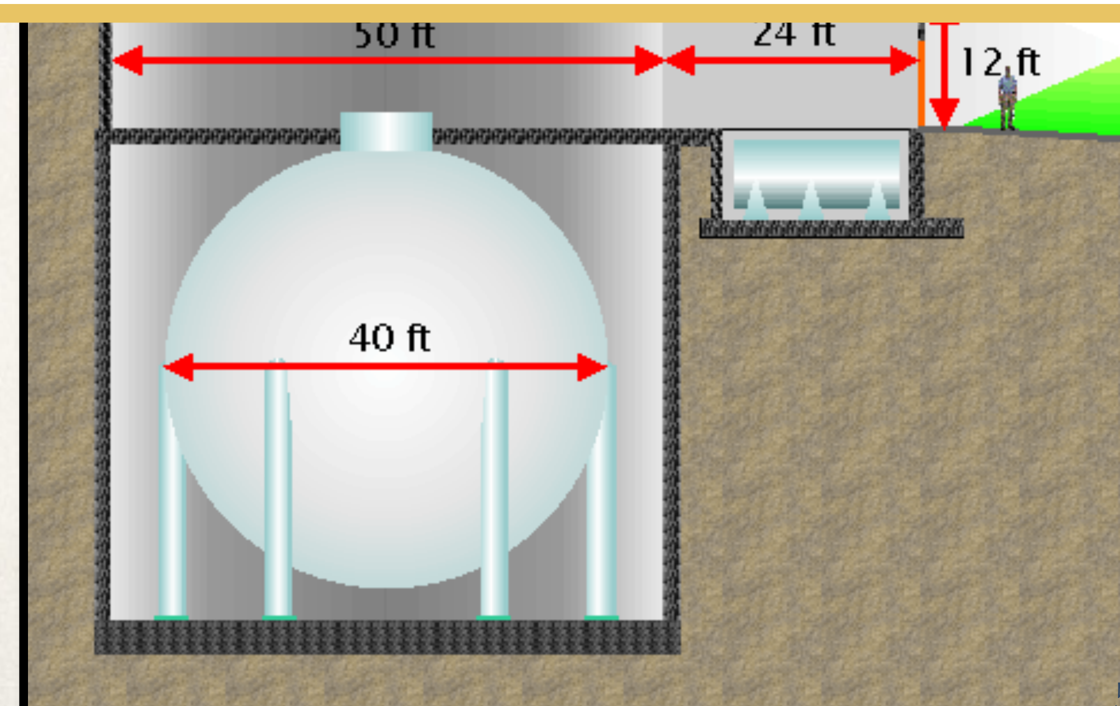
MiniBooNE: Detector



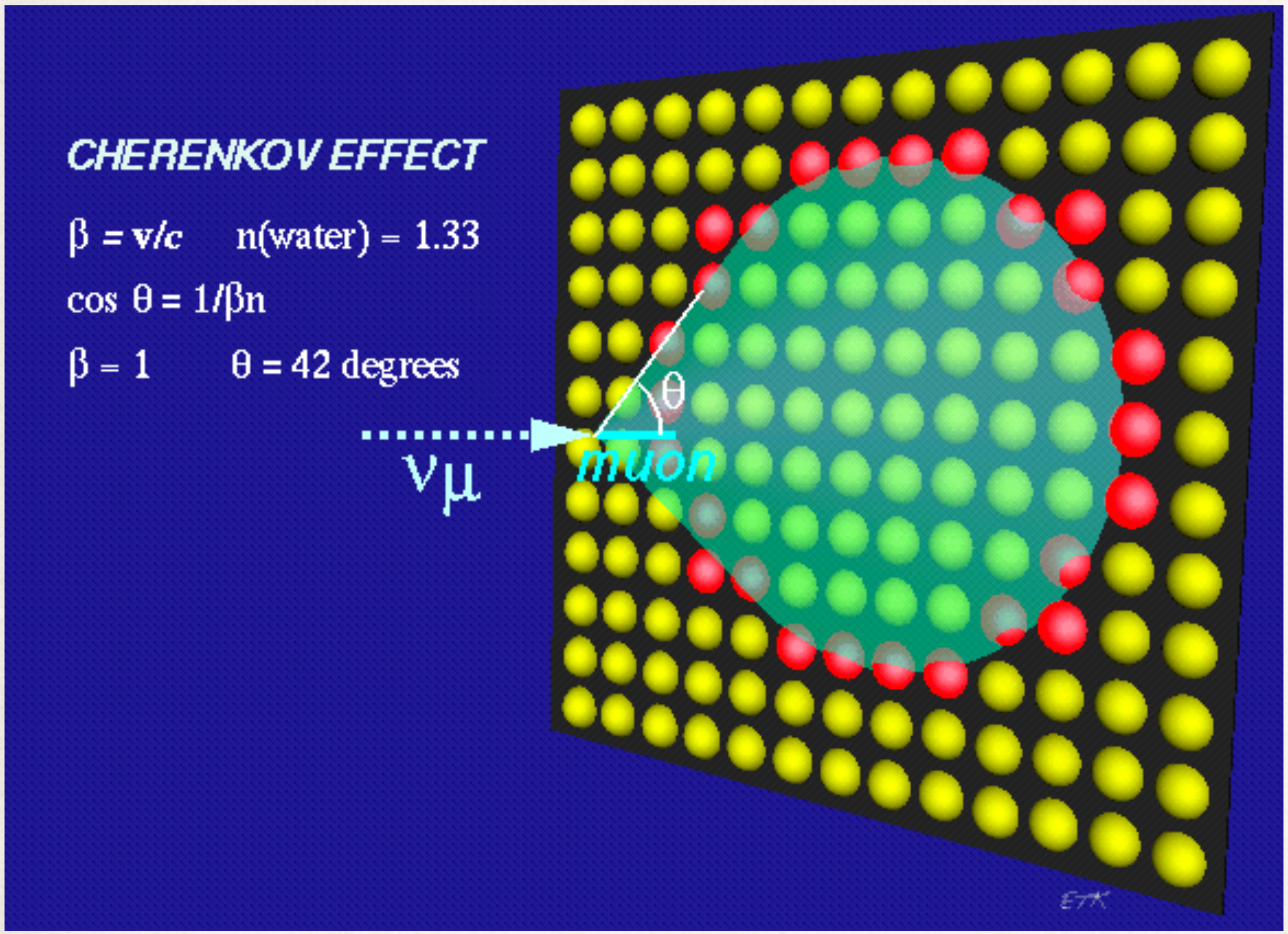
- Cherenkov detector; 12.2 m diameter sphere filled with mineral oil
- Designed to study short-baseline ν

Question for the audience: How does a Cherenkov detector work?

- Fermilab Booster ν beam: $\langle E_\nu \rangle \sim 700$ MeV, ideally suited for studying quasi-elastic scattering
- Very large datasets and full angular coverage



MiniBooNE: Detector

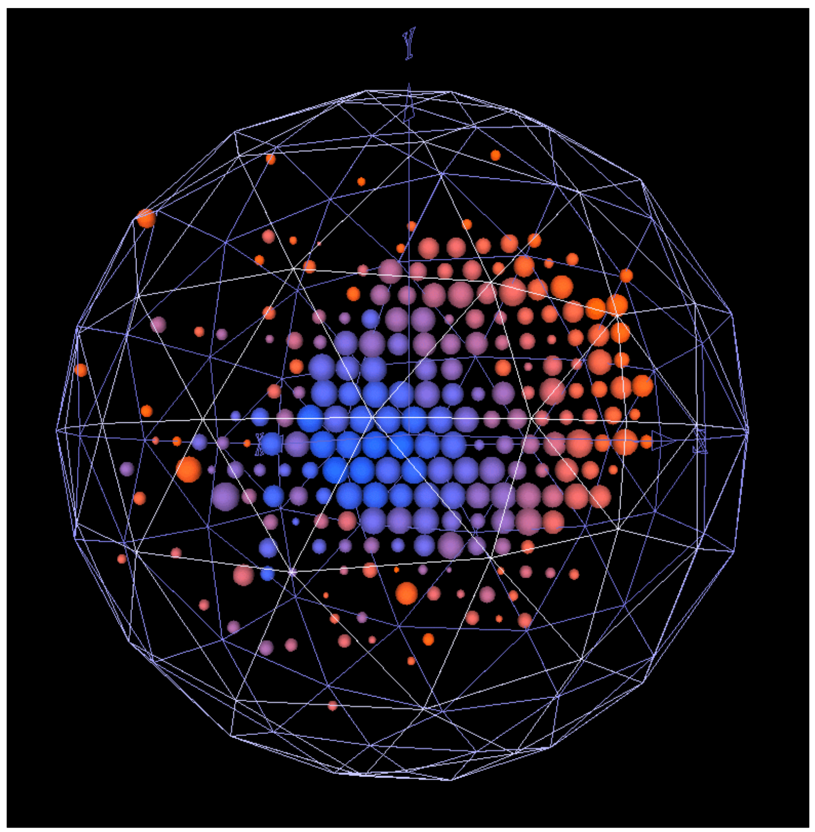


hep.bu.edu

- Cherenkov detectors look at Cherenkov radiation produced when particles travel faster than the speed of light in a material

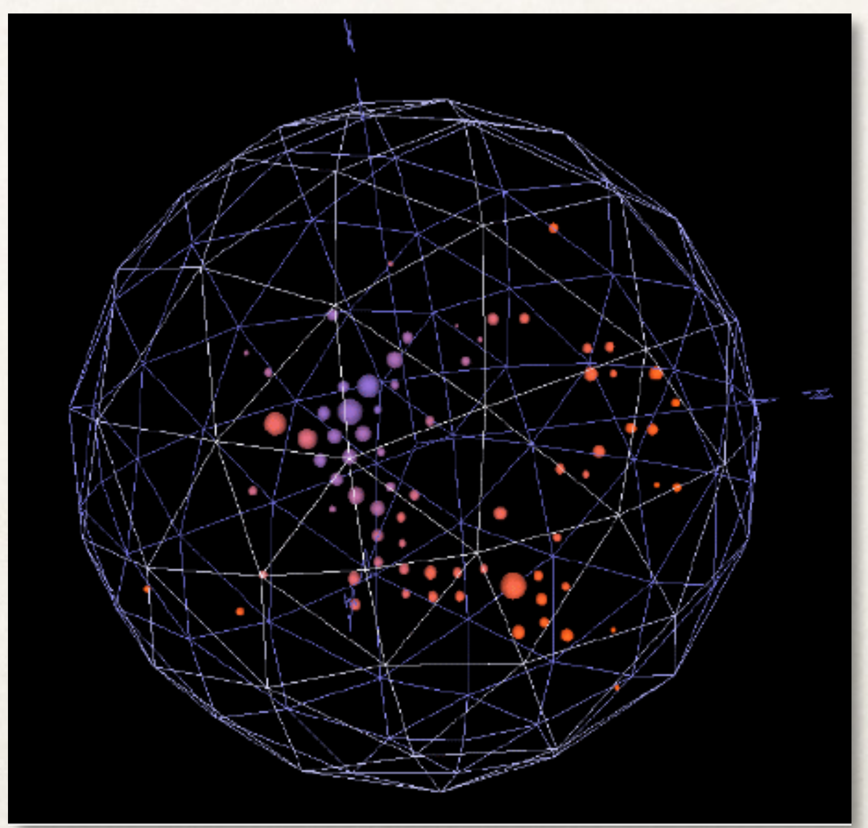
- Cones of light appear as rings that can be used to identify and measure the energy and angle of high velocity particles

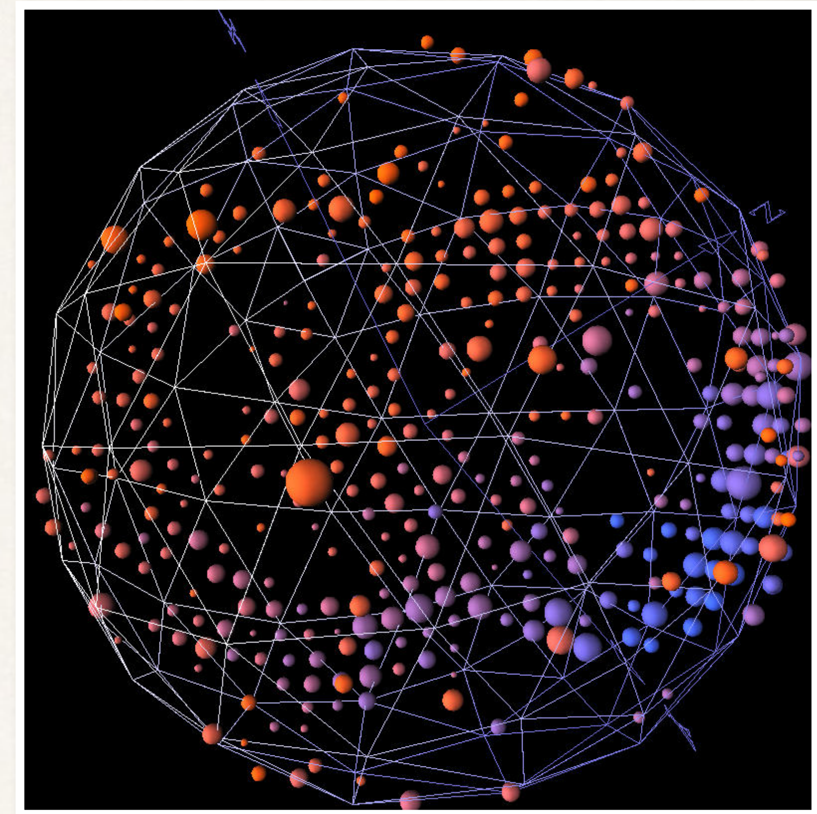
What Interactions Look Like In MiniBooNE



Muon Candidate
(also see Michel
decay electron)

Electron
Candidate



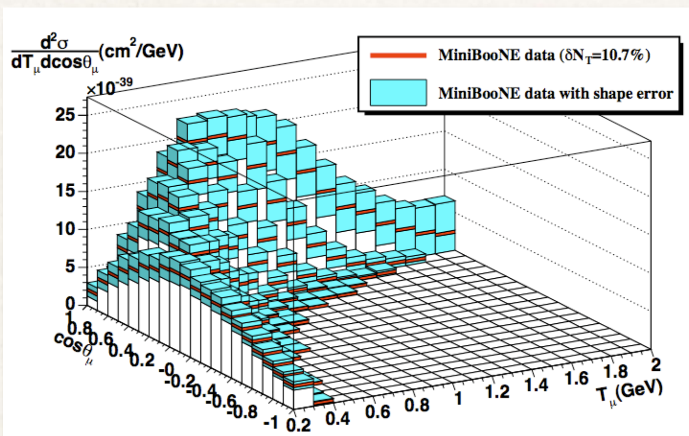


$\pi^0 \rightarrow \gamma\gamma$
Candidate

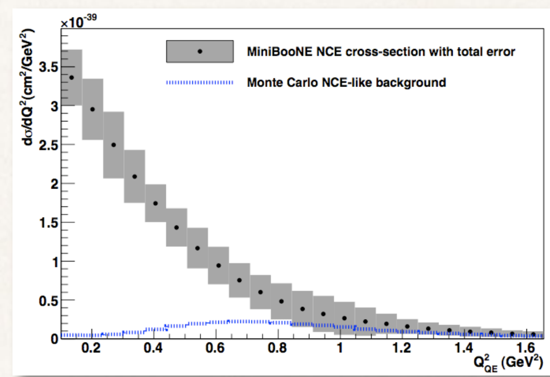
MiniBooNE: Results

Has published cross sections for > 90% of beam

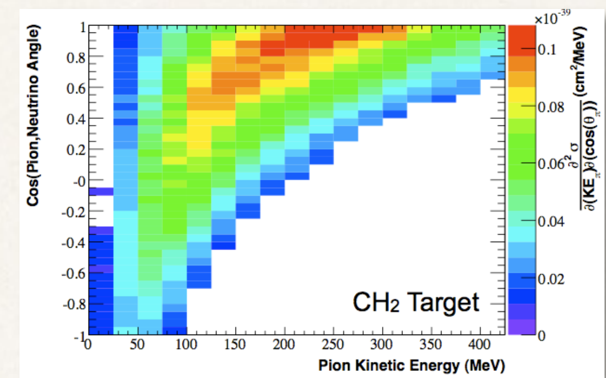
- First time in history for full kinematics (diff'l and double diff'l cross sections) have been reported for these processes; total of 11 cross section publications



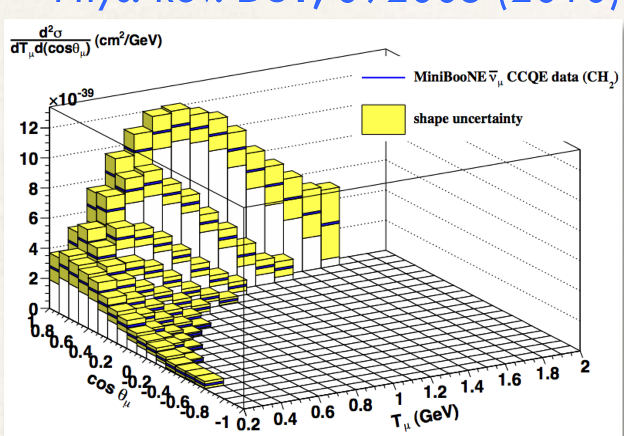
ν quasi-elastic scattering
- Phys. Rev. Lett. **100**, 032301 (2008)
- Phys. Rev. **D81**, 092005 (2010)



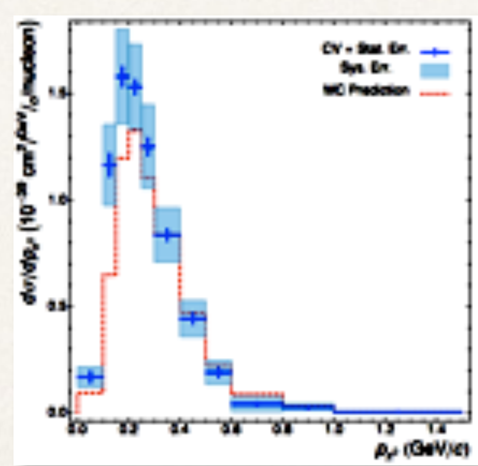
ν and ν NC elastic scattering
- Phys. Rev. **D82**, 902005 (2010)
- arXiv:1309.7257



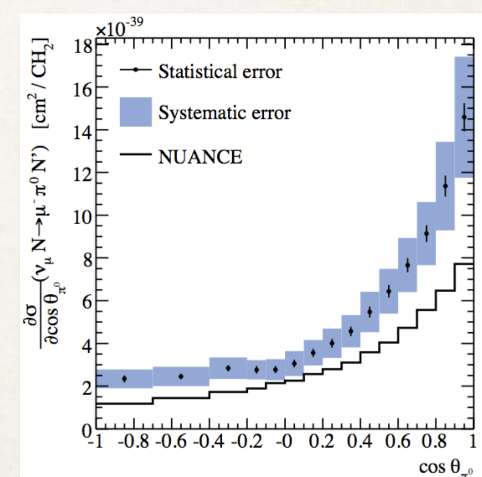
CC π^+ production
- Phys. Rev. Lett. **103**, 081801 (2009)
- Phys. Rev. **D83**, 052007 (2011)



ν quasi-elastic scattering
- Phys. Rev. **D84**, 072005 (2011)
- Phys. Rev. **D88**, 032001 (2013)



NC π^0 production
- Phys. Lett. **B664**, 41 (2008)
- Phys. Rev. **D81**, 013005 (2010)

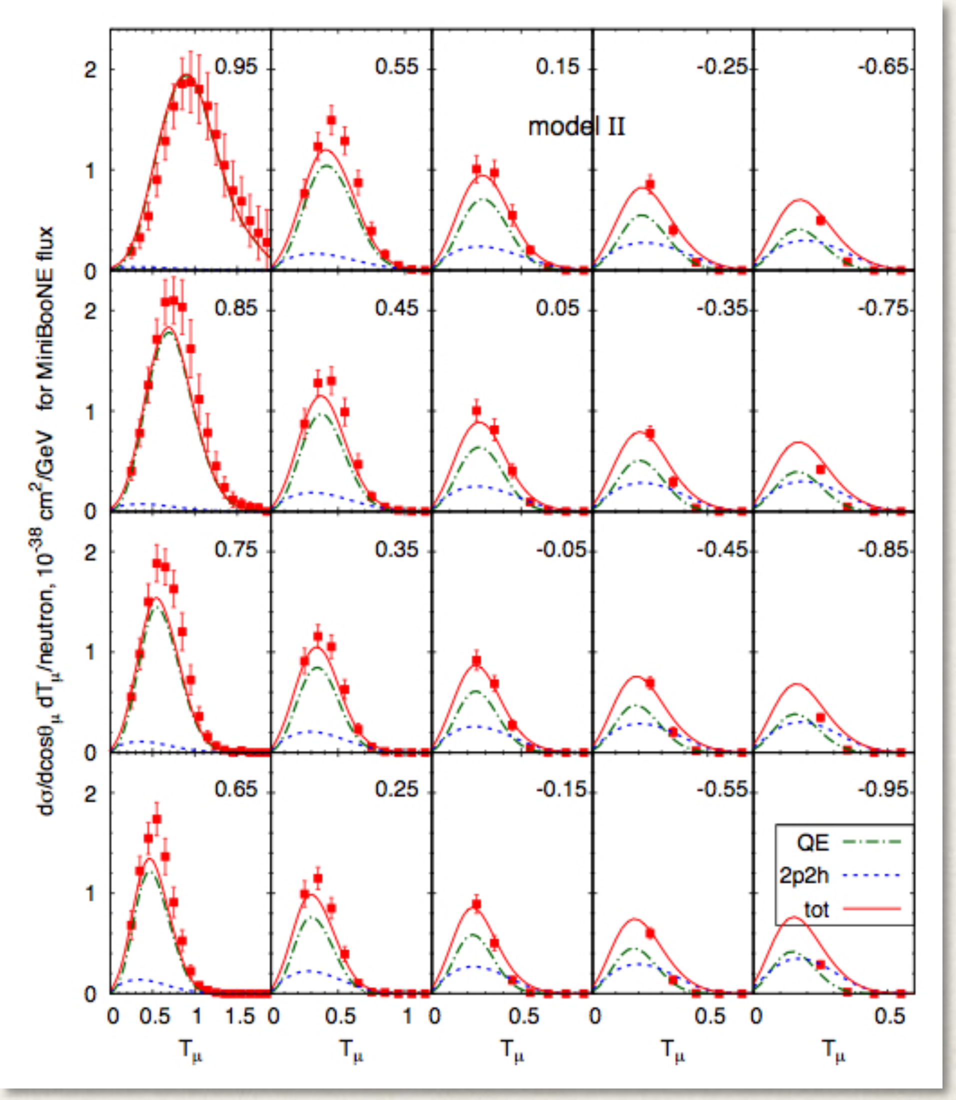


CC π^0 production
- Phys. Rev. D83, 052009 (2011)

MiniBooNE: Results

- A recent example: Quasi-elastic scattering
  - First experiment to look at 2-D distribution of muon energy and angle
  - Show sharp discrepancies with conventional quasi-elastic model
  - Appears consistent with models in which neutrinos interact on correlated pairs of nucleons rather than just individual nucleons

Lalakulich, Gallmeister, Mosel, arXiv:1203.2935



Neutrino Scattering Data:

MINERvA

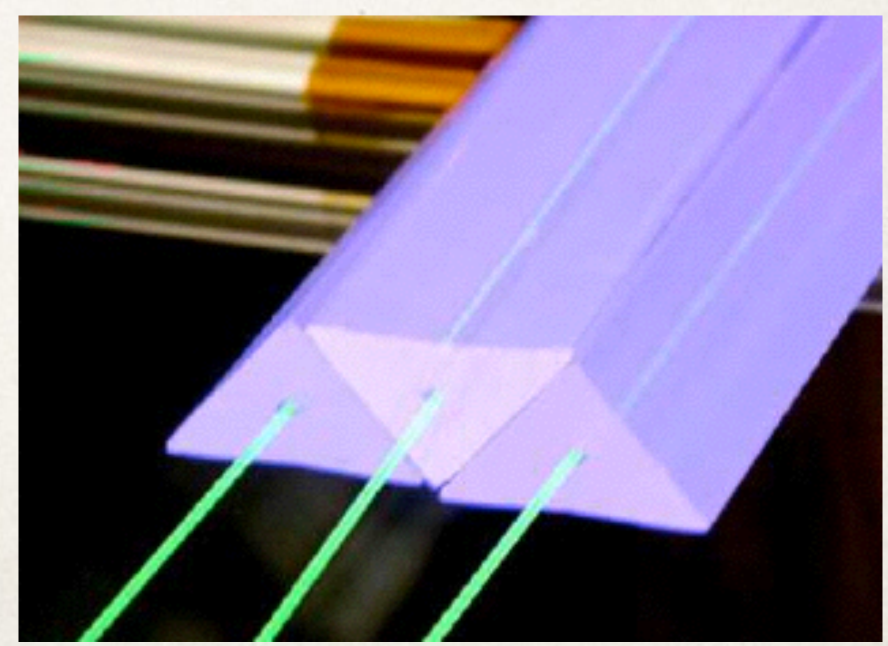
MINERνA: Detector

- Made of > 30,000 strips of plastic scintillator interspersed with other materials

- Located in NuMI beam at Fermilab upstream of the MINOS near detector, which is used to measure the charge and momentum of muons exiting the back of MINERvA

- Higher energy than MiniBooNE $\langle E_\nu \rangle \sim 3.5$ GeV (similar to LBNE)

- High statistics; Optimized for both tracking and calorimetry; limited angular acceptance

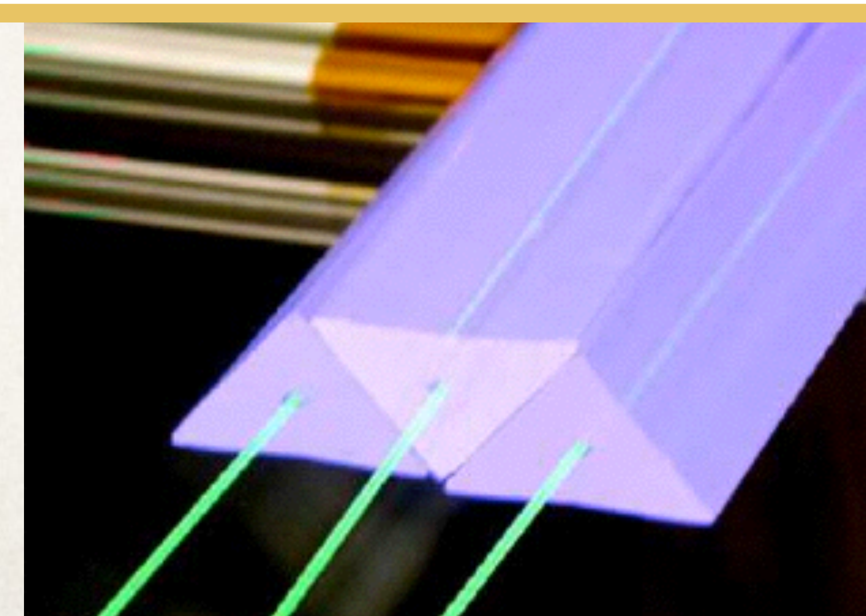


MINERνA: Detector

- Made of > 30,000 strips of plastic scintillator interspersed with other materials

- Located in NuMI beam at Fermilab upstream of the MINOS near detector, which is used to

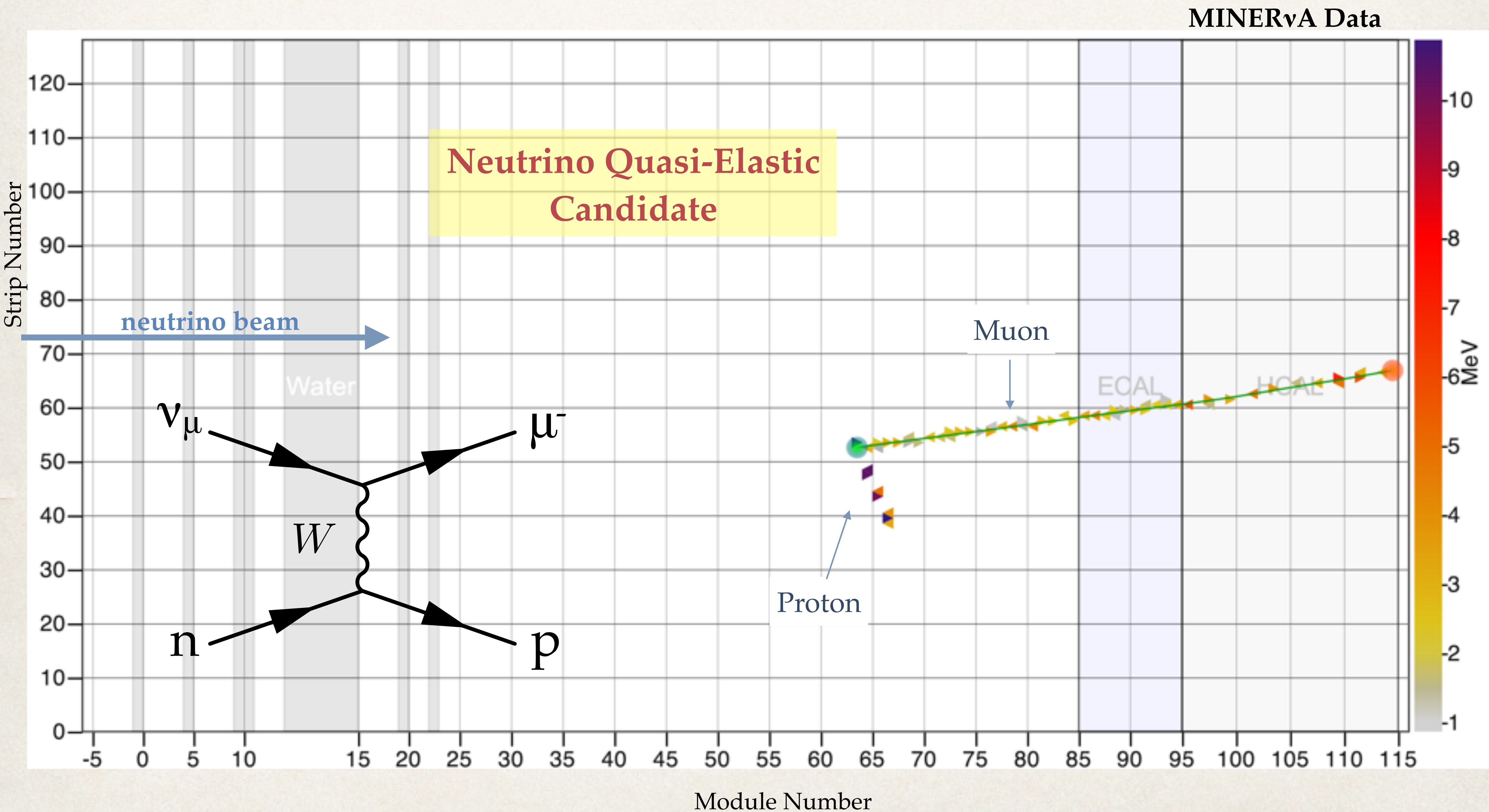
Question for the audience: What is scintillator?



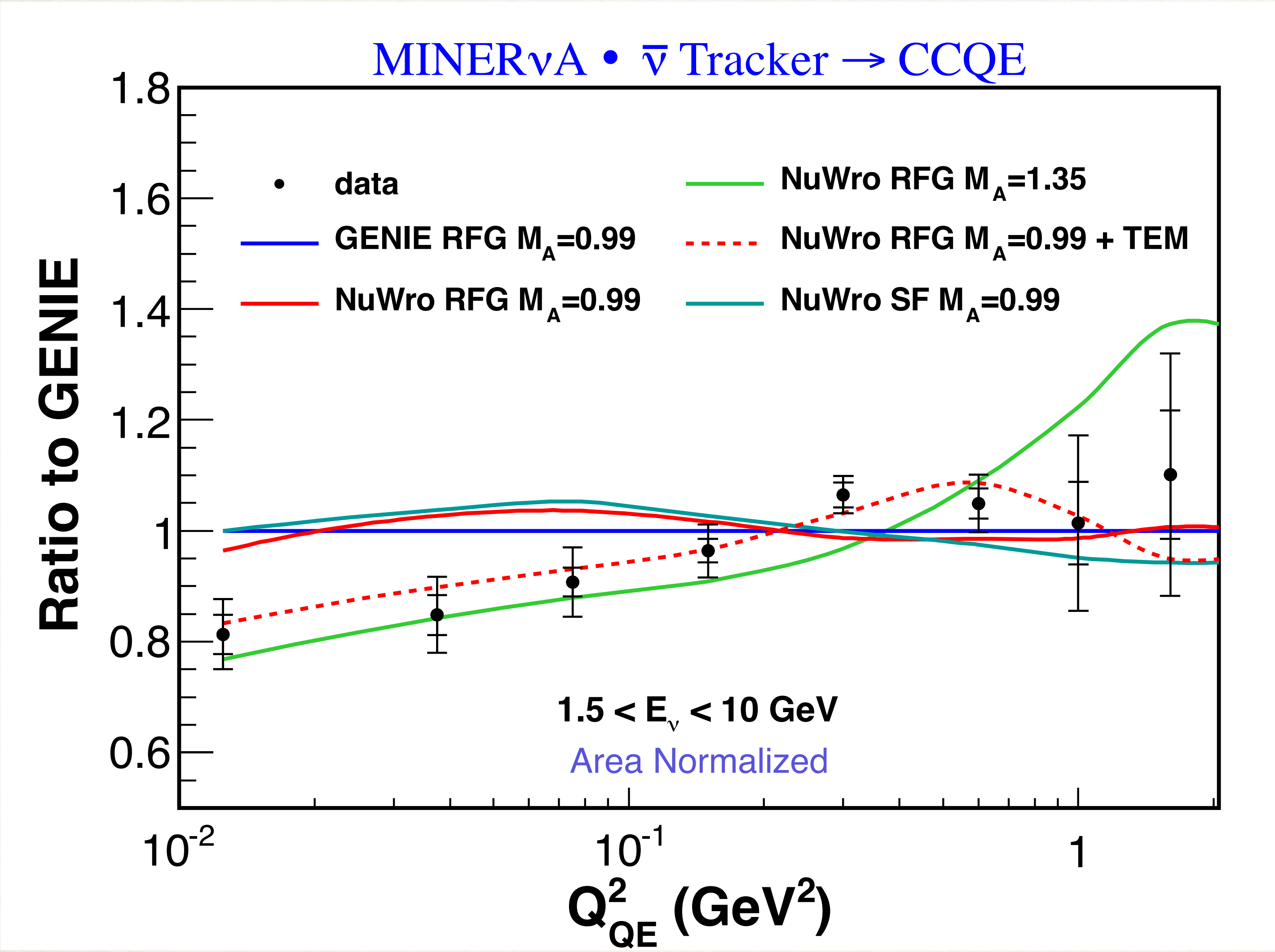
- Higher energy than MiniBooNE $\langle E_\nu \rangle$ ~ 3.5 GeV (similar to LBNE)

- High statistics; Optimized for both tracking and calorimetry; limited angular acceptance

What Interactions Look Like In MINERνA



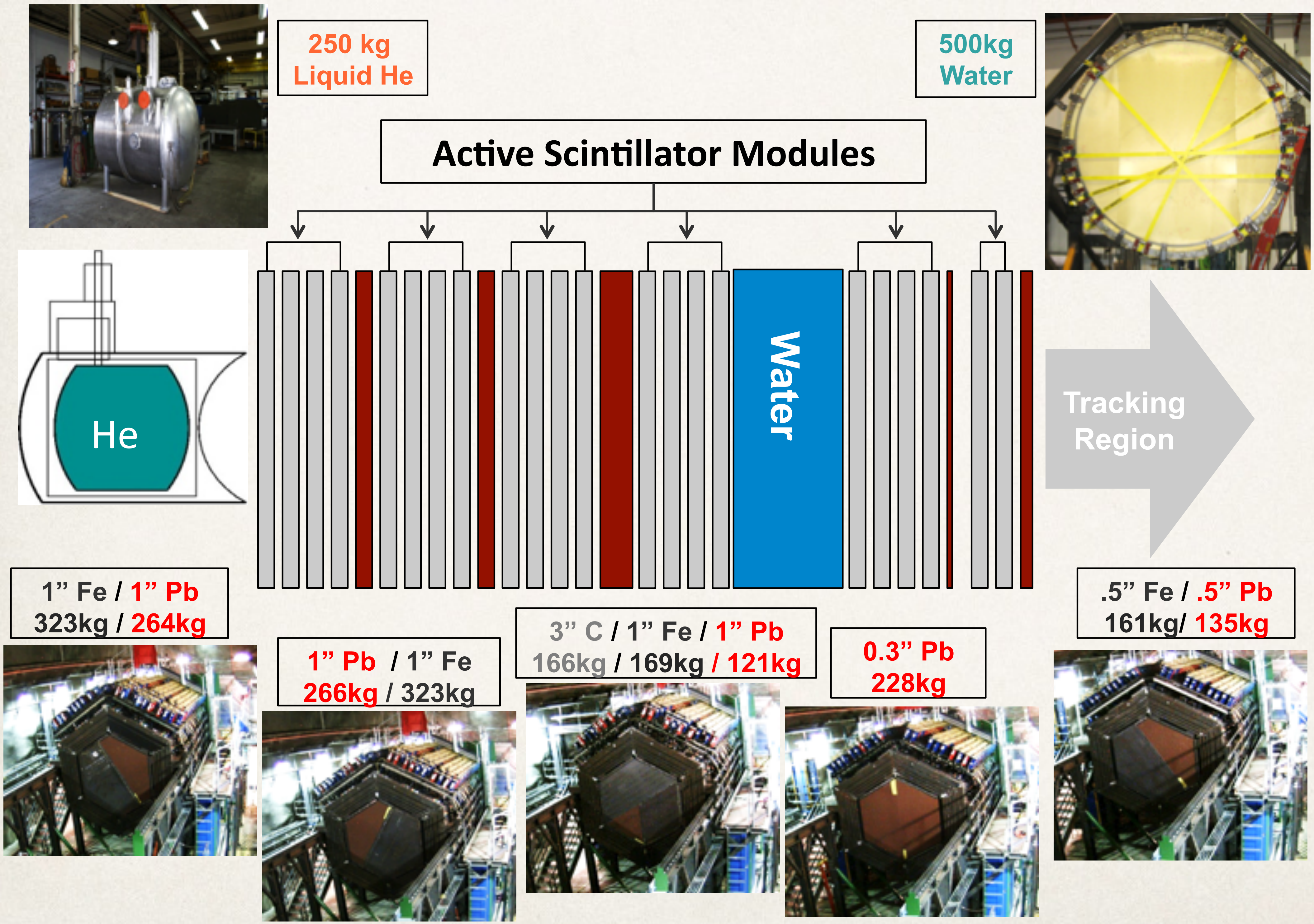
MINERνA: Results



- The quasi-elastic cross sections you saw a few slides ago, compared with many models

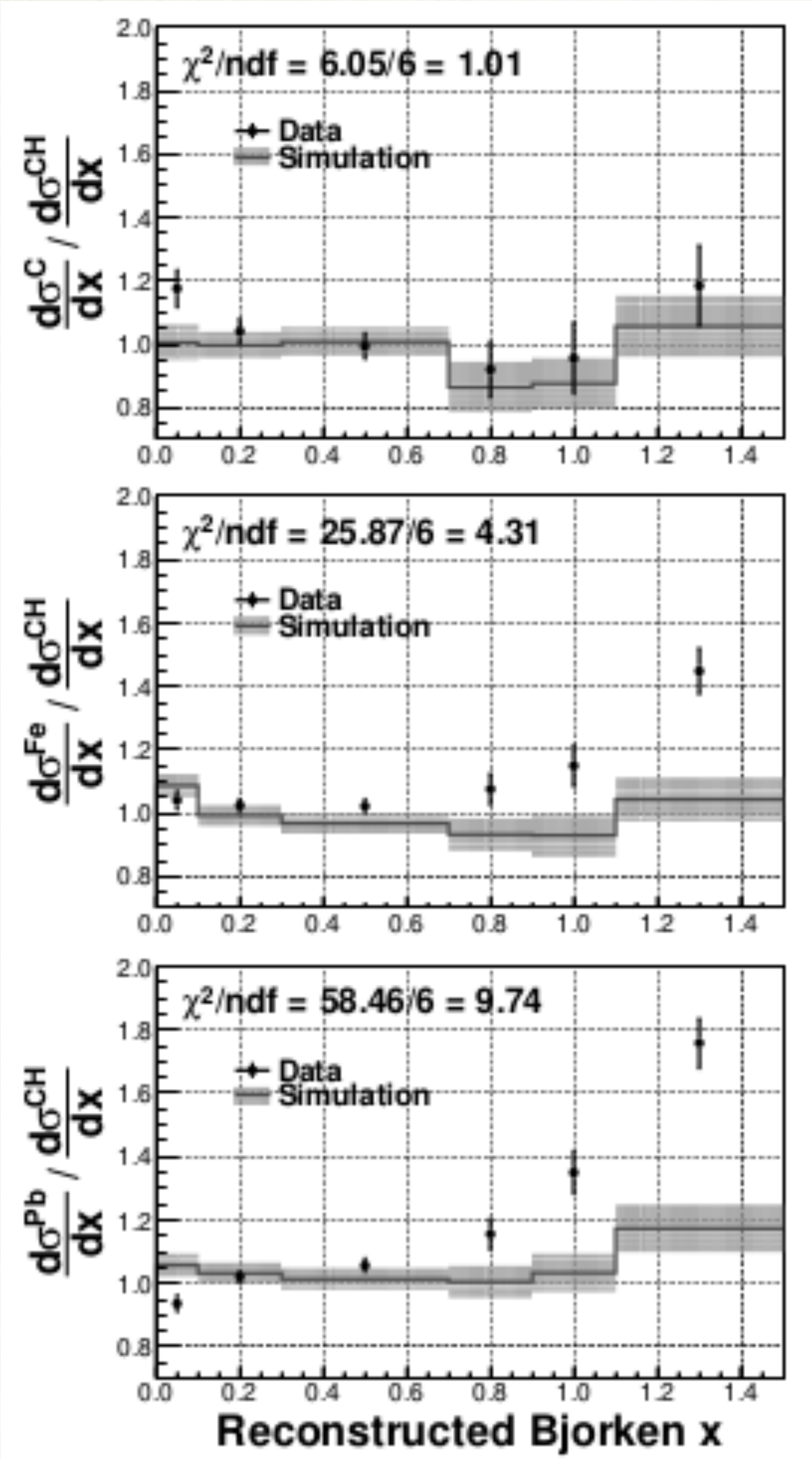
- The blue line is the model of QE scattering that was used for decades, is disfavored by the data
- The green line shows a simple modification of this model similar to what's used by most oscillation experiments currently
- The dotted red line shows a model that includes neutrino interactions on correlated pairs of nucleons
- Both MINERvA and MiniBooNE indicate that interactions on multi-nucleon bound states are significant and must be incorporated into models

MINERvA: Nuclear Ratios



MINERvA has also begun to study the ratio of neutrino interactions on different nuclei using solid nuclear targets.

MINERvA: Nuclear Ratios



Carbon

Iron

Lead

arXiv:1403.2103 [hep-ex]

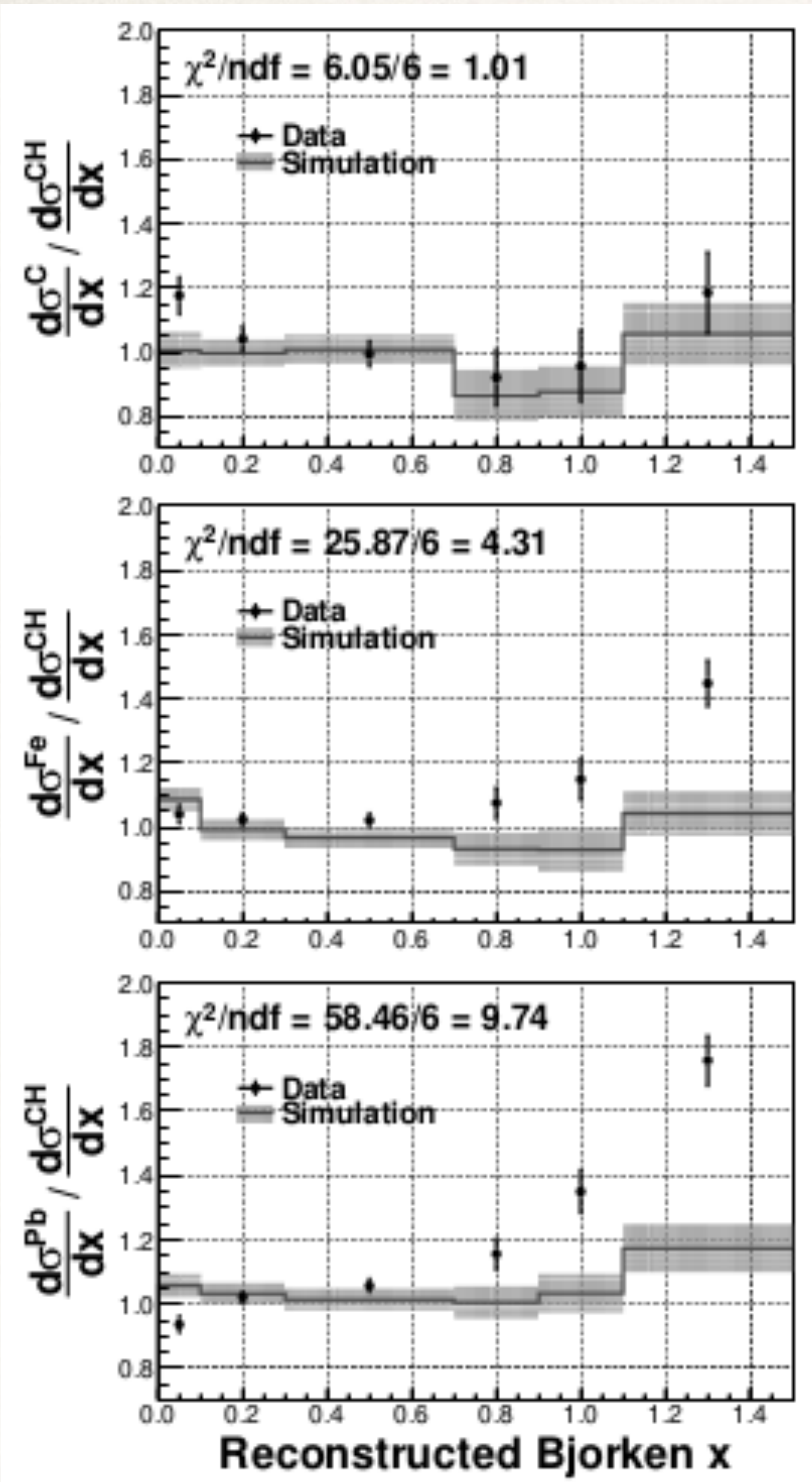
- Charged current cross section ratios of a dimensionless scaling variable called "x"
- x corresponds to the fraction of the initial nucleon's momentum that is carried by the struck quark
- Large normalization uncertainties cancel in ratios

$$x = \frac{Q^2}{2M\nu}$$

$$\nu = E_\nu - E_\mu$$

$$Q^2 = 2E_\nu\left(E_\mu - p_\mu cos\left(\theta_\mu\right)\right)$$

MINERvA: Nuclear Ratios



arXiv:1403.2103 [hep-ex]

Carbon

Iron

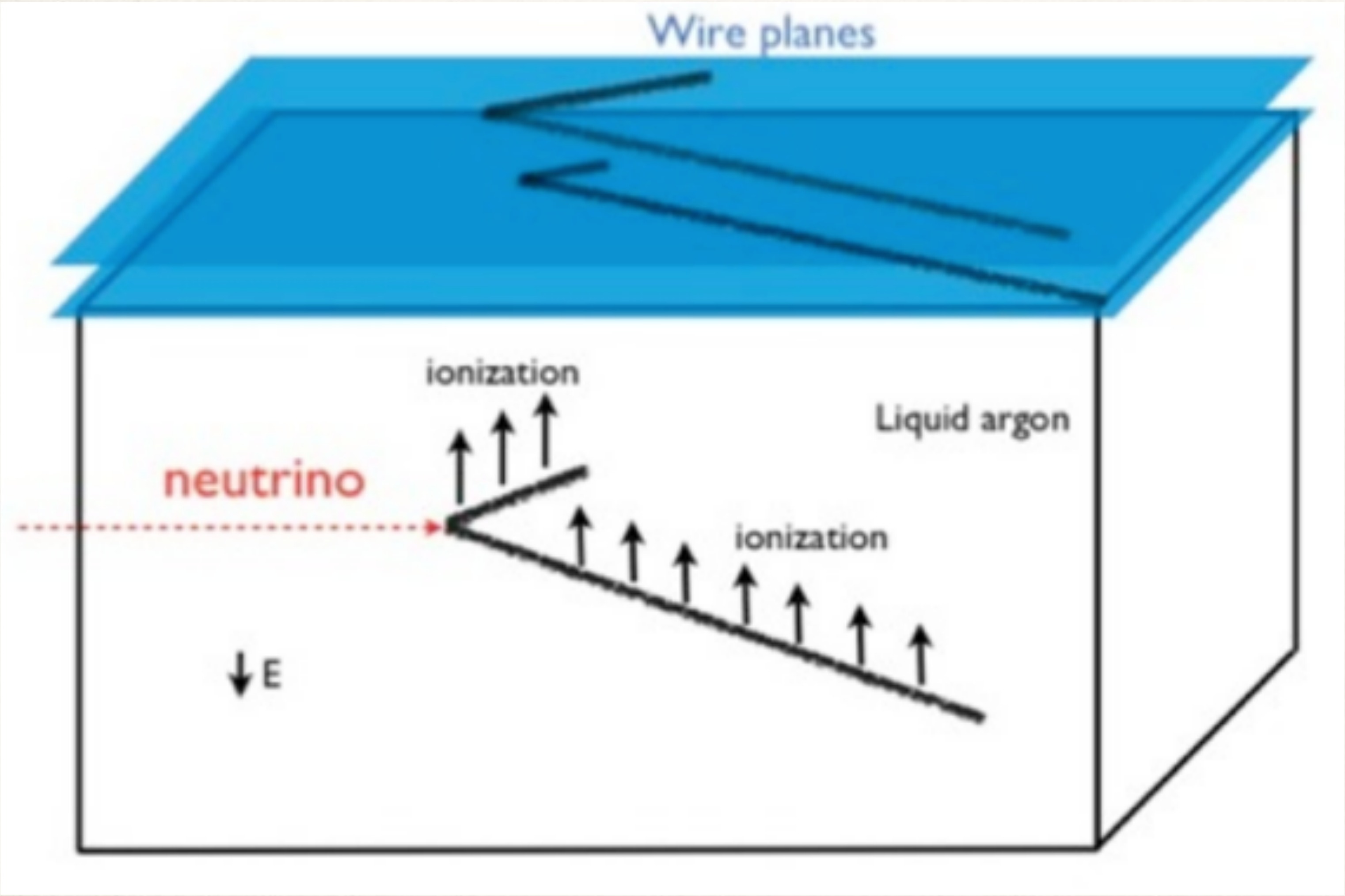
Lead

- Again the accepted model of nuclear effects is wrong
- And it is **increasingly wrong in heavier nuclei**
- Not just important for oscillation experiments
  - This is **physics we don't understand**

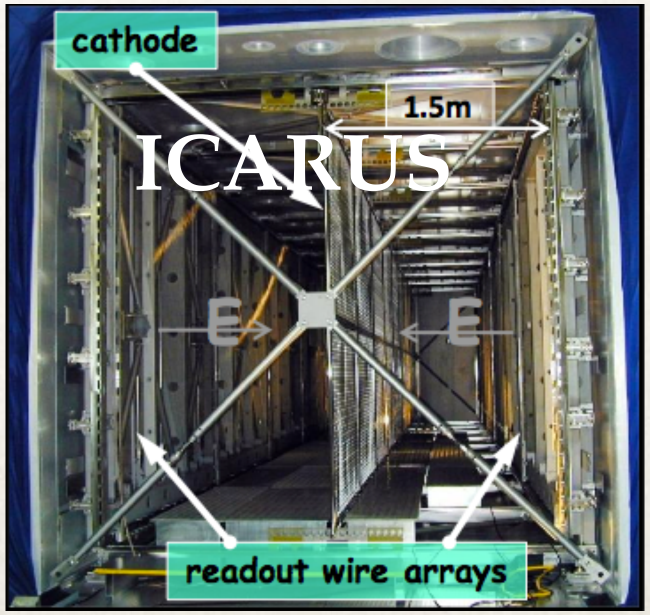
Neutrino Scattering Data:

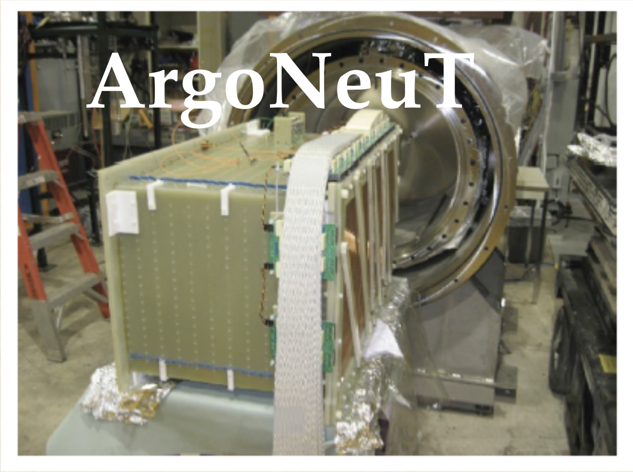
Liquid Argon Detectors

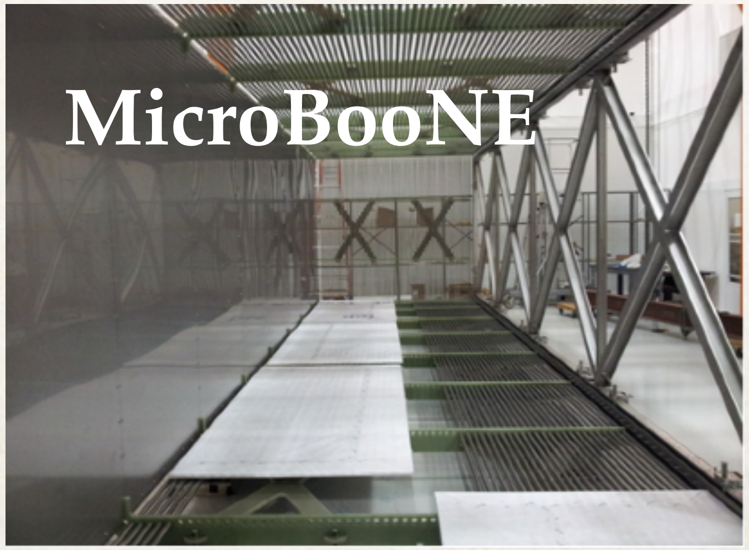
Liquid Argon Detectors



- Time project chambers
- Dense material provides many neutrino interactions
- Is the planned technology of the LBNE far detector

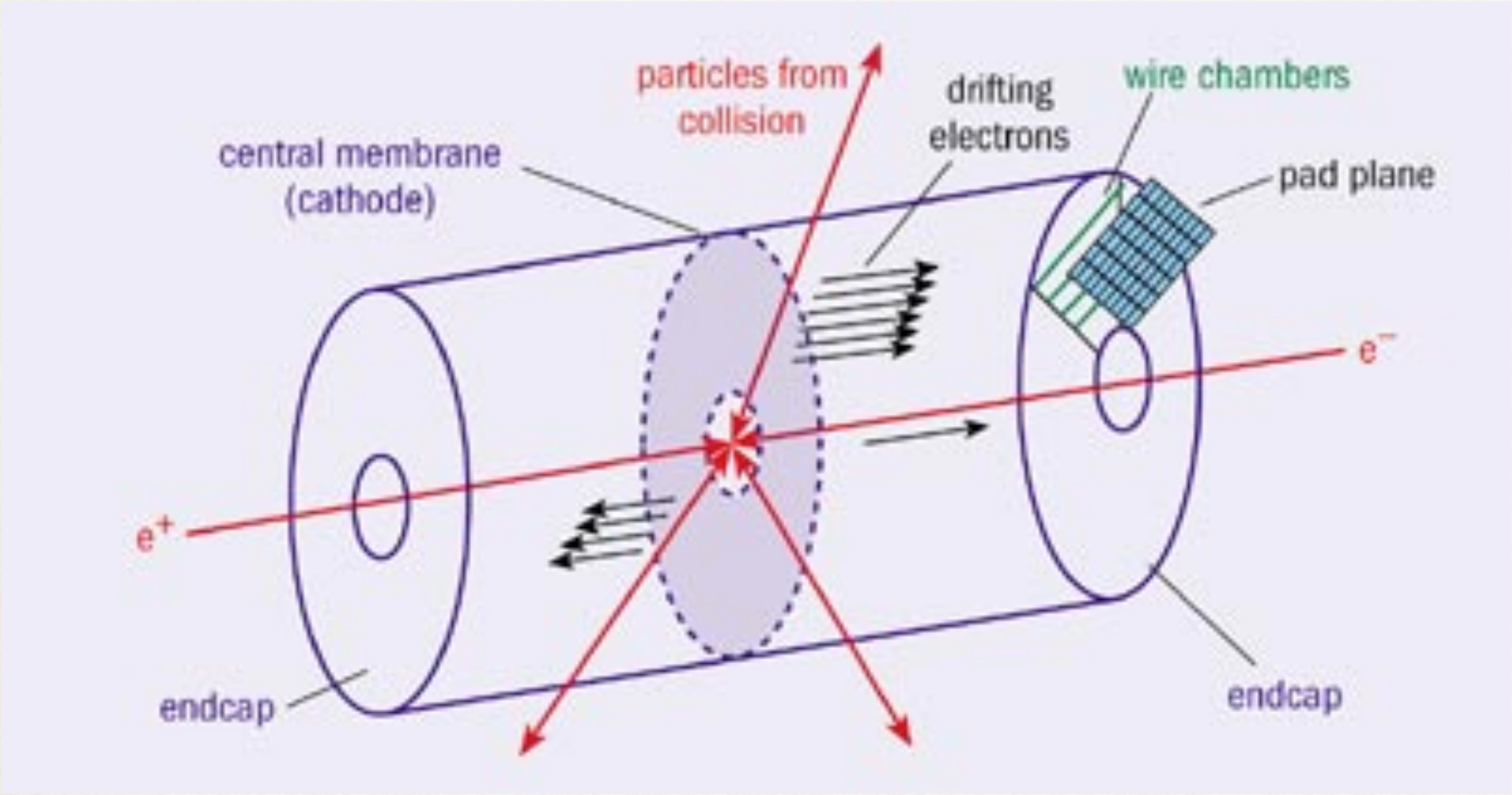






Liquid Argon Detectors

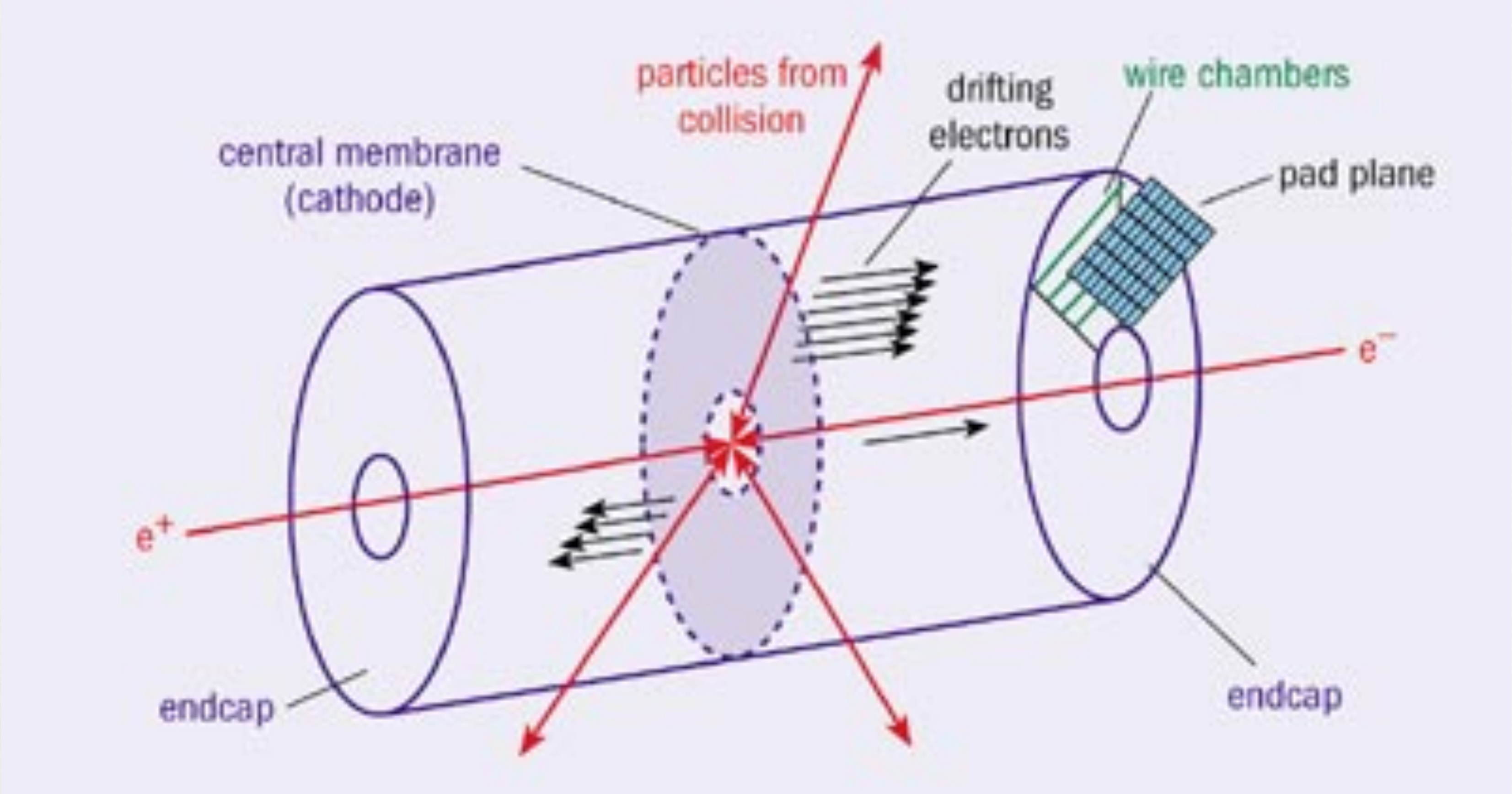
- More on TPC's (Time Projection Chambers)



- Charged particles ionize gas (or liquid) as they travel through the chamber
- Ions and electrons are sucked (by an electric field) to detectors at the ends of the chamber.

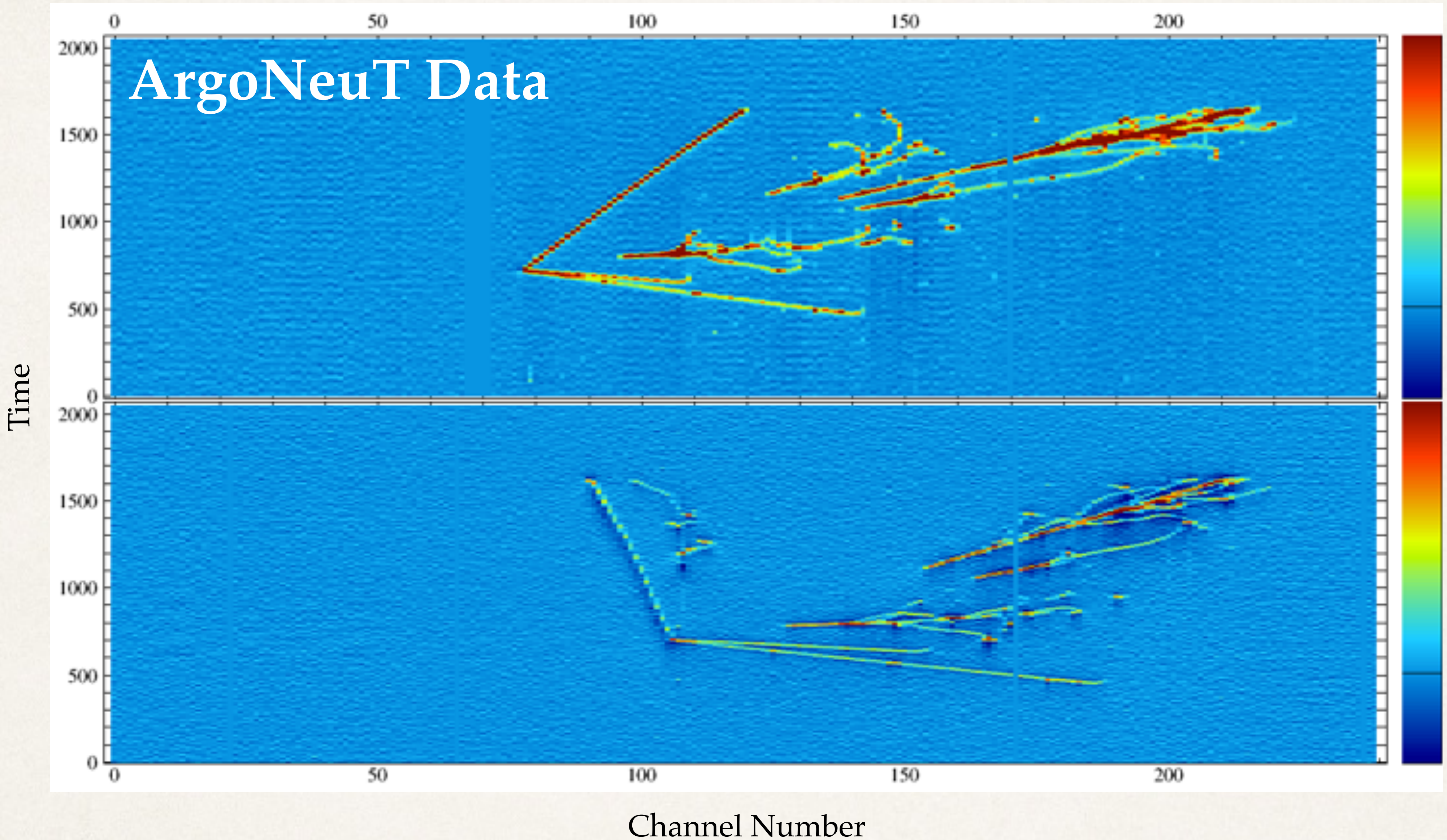
Liquid Argon Detectors

- More on TPC's (Time Projection Chambers)



- The transverse position of the original ionization is (mostly) preserved during the "sucking"
- The time of flight gives you a good longitudinal position
- So TPC's have excellent 3-D position resolution

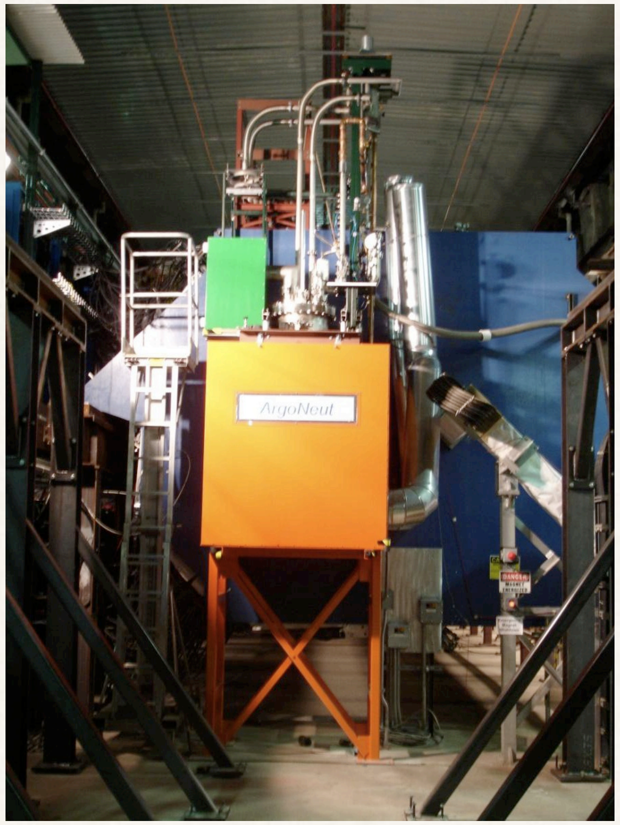
What Interactions Look Like In Argon

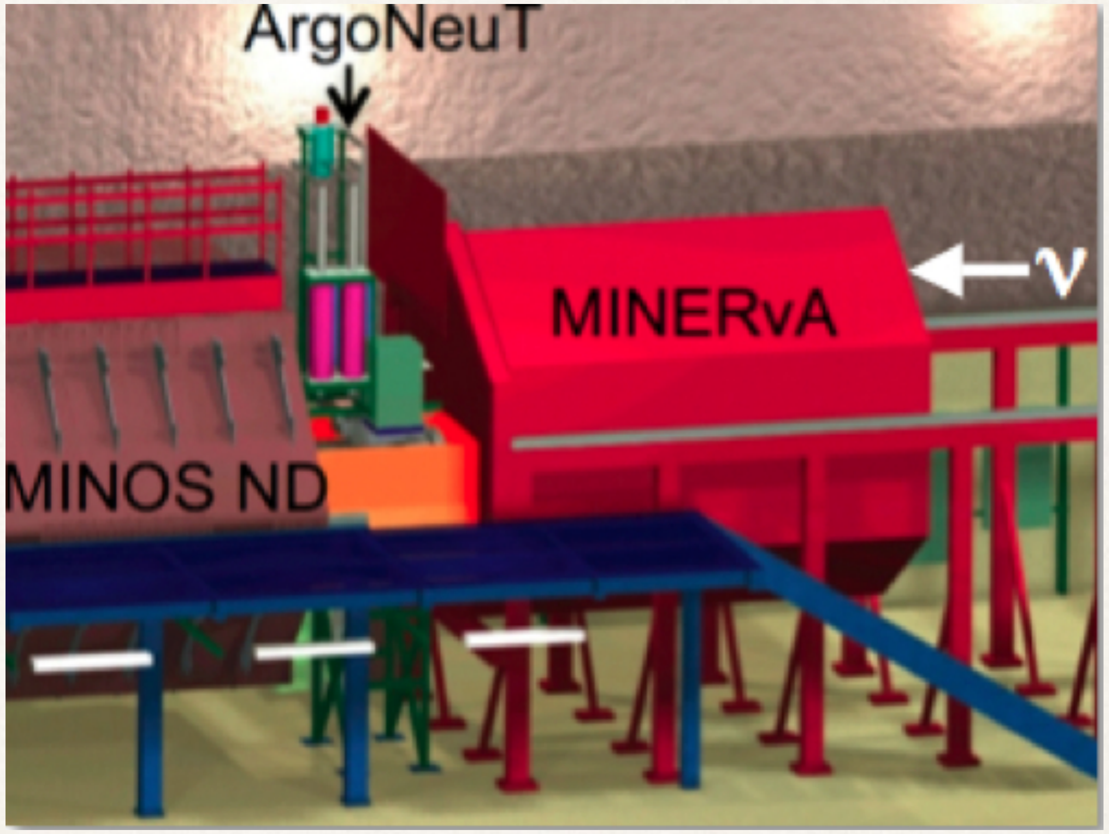


- More detail than any type of neutrino detector since bubble chambers

- Lots of information — a big reconstruction challenge!

ArgoNeuT: Detector

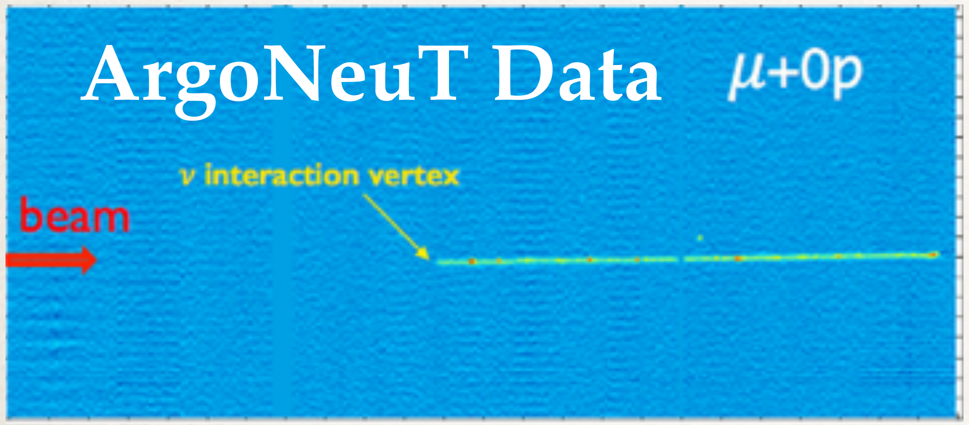


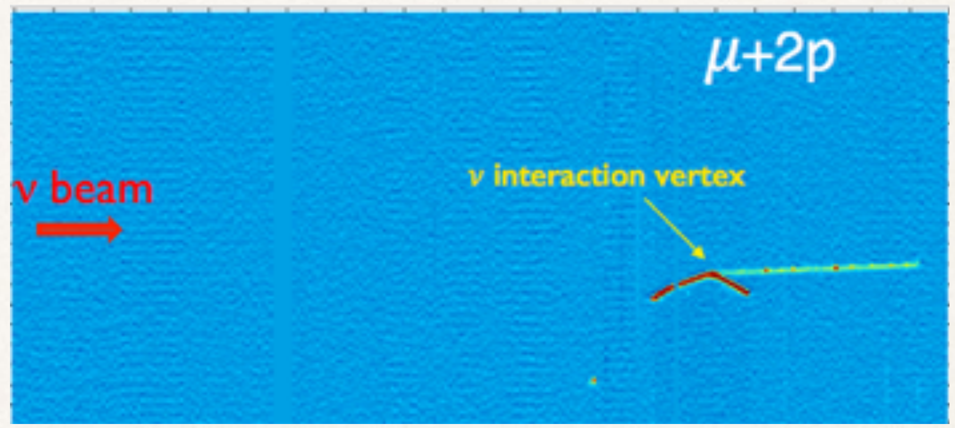


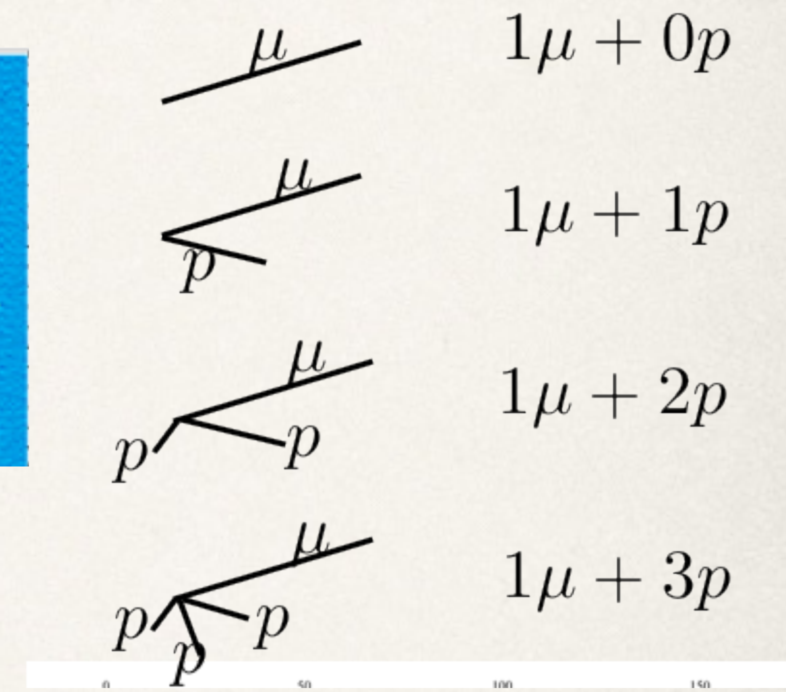
- ArgoNeuT was the first liquid argon TPC in a U.S. neutrino beam (NuMI) — similar energy to MINERvA
- Was located between MINERvA and MINOS detectors (also used MINOS detector as a muon spectrometer)
- Small data sample, but able to study sample in fine detail

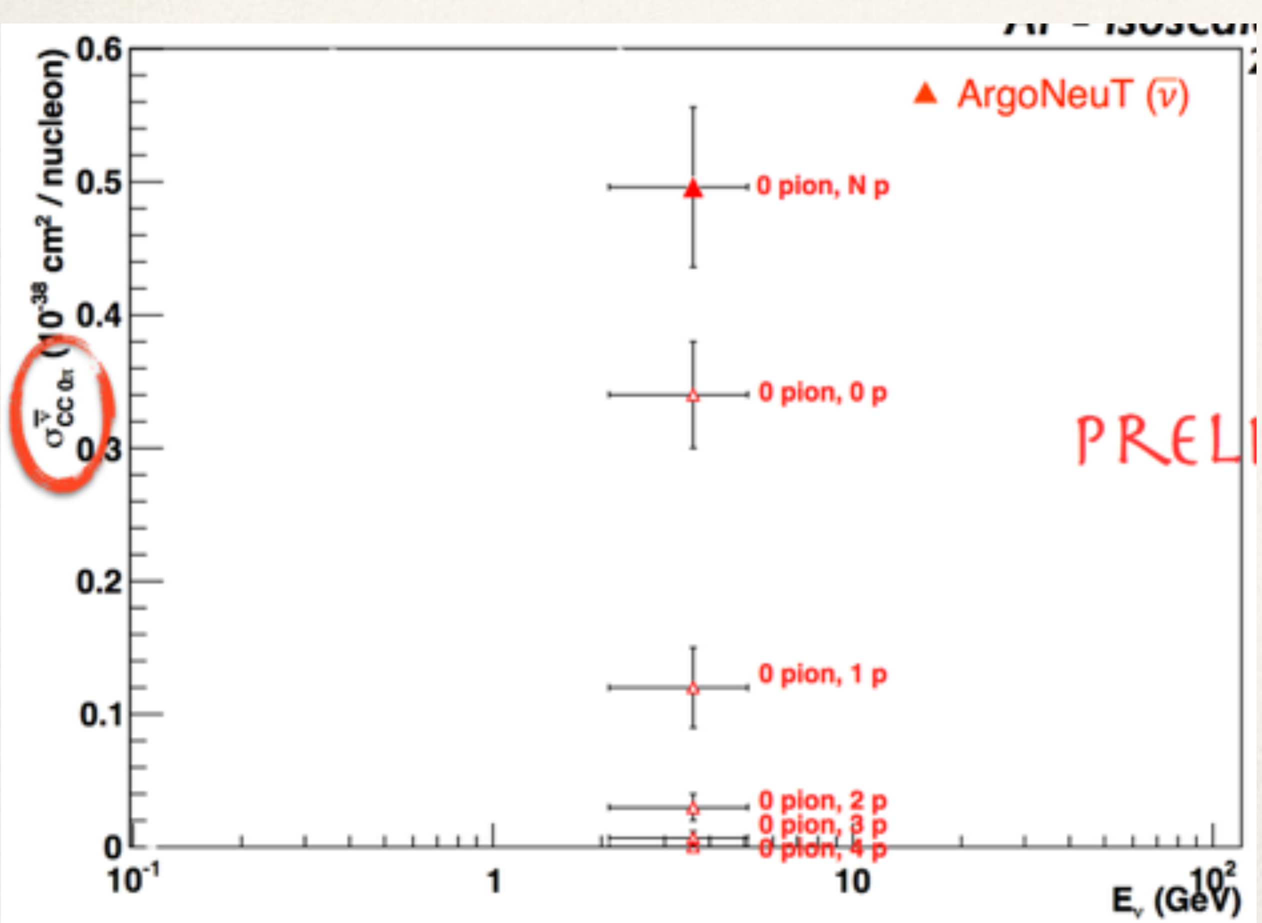
ArgoNeuT: Results

Liquid argon is excellent for studying particle multiplicity









- Can measure QE-like events in ways that no one has before, due to high level of detail available in liquid Argom

O Palamara, INT Worksop 2013

MicroBooNE: Detector

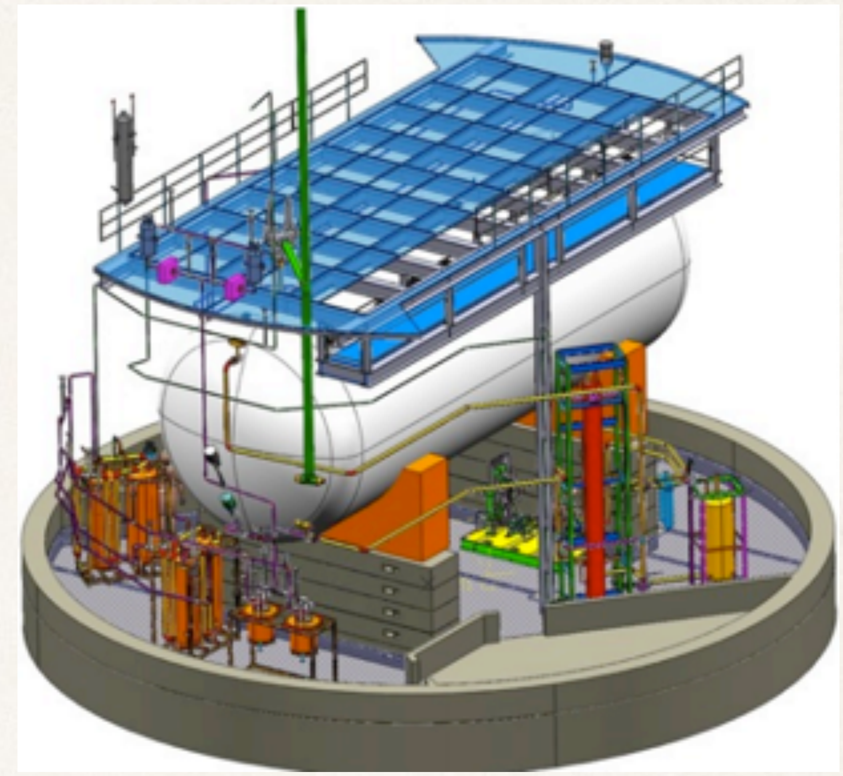
The next step in liquid argon neutrino detection:

- 170 Ton liquid argon TPC
- In Booster beam at Fermilab, very near MiniBooNE location

- Will accumulate many more statistics than ArgoNeuT
- Will also see lower energy beam

MicroBooNE: Status

- Will begin taking data this year
- ~143,000 neutrino interactions in 2-3 years
- There are also several other proposals to use LAr detectors to measure cross sections (LAr1ND, ICARUS, CAPTAIN,…)



NUANCE

production mode	formula	#evt ($\times 10^3$)
CC quasi-elastic	$\nu_\mu + n \rightarrow \mu^- + p$	66
NC elastic	$\nu_\mu + N \rightarrow \nu_\mu + N$	21
CC resonance π^+	$\nu_\mu + N \rightarrow \mu^- + N + \pi^+$	28
CC resonance π°	$\nu_\mu + n \rightarrow \mu^- + p + \pi^\circ$	7
NC resonance π°	$\nu_\mu + N \rightarrow \nu_\mu + N + \pi^\circ$	8
NC resonance $\pi^\pm$	$\nu_\mu + N \rightarrow \nu_\mu + N' + \pi^\pm$	3
CC DIS	$\nu_\mu + N \rightarrow \mu^- + X, W > 2$ GeV	1
NC DIS	$\nu_\mu + N \rightarrow \nu_\mu + X, W > 2$ GeV	0.5
CC coherent π°	$\nu_\mu + A \rightarrow \mu^- + A + \pi^+$	3
NC coherent $\pi^\pm$	$\nu_\mu + A \rightarrow \nu_\mu + A + \pi^\circ$	2
CC Kaon production	$\nu_\mu + N \rightarrow \mu^- + K + X$	~0.1
NC Kaon production	$\nu_\mu + N \rightarrow \nu_\mu + K + X$	<0.1
others		4
total		143

6.6e20 POT (2-3 years of running)

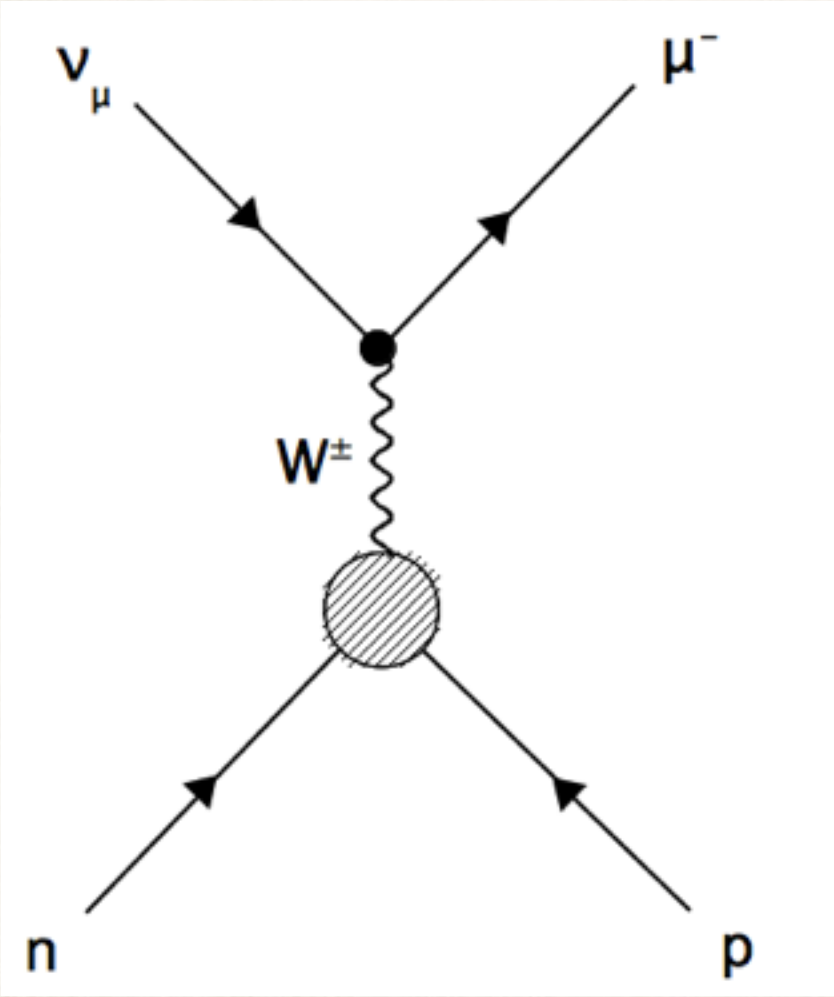
Conclusion

- If you care about the future of accelerator-based neutrino measurements, you care about cross section measurements
- Neutrino interactions in the region of interest to oscillation experiments are complex and interesting
- Consider getting involved in one of the ongoing cross section programs at Fermilab:

Backup

Quasi-Elastic Scattering

Neutrino-nucleon quasi-elastic scattering:



$$\nu_l + n \to l^- + p$$
$$\bar{\nu}_l + p \to l^+ + n$$

- Commonly used as a signal channel in oscillation measurements
  - Clean experimental signature
  - Identifies neutrino flavor
  - Kinematics can be reconstructed (assuming a nucleon at rest) using lepton measurement alone:

$$E_\nu^{QE} = \frac{m_n^2 - (m_p - E_b)^2 - m_\mu^2 + 2(m_p - E_b)E_\mu}{2(m_p - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$

Q = Four momentum transferred to the nucleon → $Q^2_{QE} = 2E_\nu^{QE}(E_\mu - p_\mu \cos\theta_\mu) - m_\mu^2$

Quasi-Elastic Scattering

Neutrino-nucleon quasi-elastic cross section:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}Q^2}_{QE}\begin{pmatrix}\nu_l n \to l^- p \\ \bar{\nu}_l p \to l^+ n\end{pmatrix} = \frac{M^2 G_F^2 \cos^2\theta_C}{8\pi E_\nu^2}\left\{A(Q^2) \mp B(Q^2)\frac{s-u}{M^2} + C(Q^2)\frac{(s-u)^2}{M^4}\right\}$$

C.H. Llewellyn Smith. Neutrino reactions at accelerator energies. Physics Reports, 3(5):261–379, June 1972.

- Sign on B term is negative for neutrinos, positive for antineutrinos
- G_F is the Fermi constant (1.17×10^{-5} GeV^{2})
- M is the average nucleon mass (939 MeV)
- θ_C is the Cabbibo angle ($\cos\theta_C = 0.9742$)
- s and u are Mandelstam variables
- E_ν is the incoming neutrino energy
- A, B and C are combinations of hadronic form factors….

Quasi-elastics are often described as "simple"…

Quasi-Elastic Scattering

Neutrino-nucleon quasi-elastic cross section:

$$A(Q^2) = \frac{m_\mu^2 + Q^2}{M^2}\left\{(1+\frac{Q^2}{4M^2})F_A^2 - (1-\frac{Q^2}{4M^2})F_1^2 + \frac{Q^2}{4M^2}(1-\frac{Q^2}{4M^2})(\xi F_2)^2 \right.$$
$$+\frac{Q^2}{M^2}Re(F_1^*\xi F_2) - \frac{Q^2}{M^2}(1+\frac{Q^2}{4M^2})(F_A^3)^2$$
$$\left. -\frac{m_\mu^2}{4M^2}\left[|F_1+\xi F_2|^2 + |F_A + 2F_P|^2 - 4(1+\frac{Q^2}{4M^2})((F_V^3)^2 + F_P^2)\right]\right\}$$

$$B(Q^2) = \frac{Q^2}{M^2}Re\left[F_A^*(F_1+\xi F_2)\right] - \frac{m_\mu^2}{M^2}Re\left[(F_1 - \tau\xi F_2)F_V^{3*} - (F_A^* - \frac{Q^2}{2M^2}F_P)F_A^3\right]$$

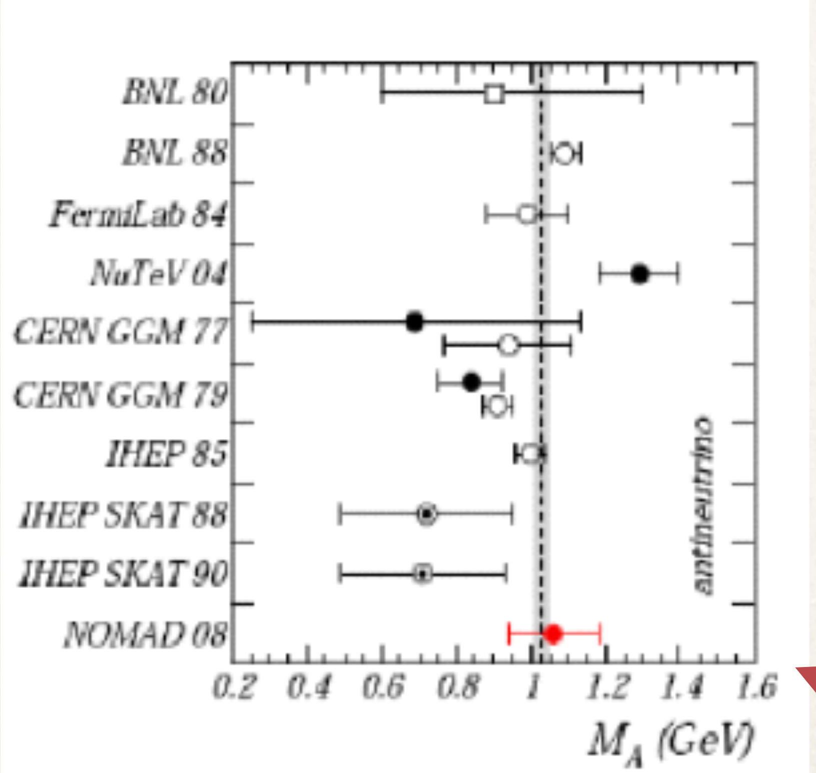
$$C(Q^2) = \frac{1}{4}\left\{F_A^2 + F_1^2 + \tau(\xi F_2)^2 + \frac{Q^2}{M^2}(F_A^3)^2\right\}$$

- Definitely not simple!
  - But actually just combinations of six form factors
    - Two vector (F_1 and F_2), an axial vector (F_A), a pseudoscalar (F_P), and two small second order terms (F_A^3 and F_V^3)

Quasi-Elastic Scattering

Neutrino-nucleon quasi-elastic cross section:

- All but the axial form factor are known from electron-nucleon scattering experiments
  - Only the F_A is most easily measured via neutrino scattering; it is typically parameterized as a dipole:



from Lyubushkin, etal [NOMAD collab] Eur.Phys.J.C63:355-381,2009

$$F_A(Q^2) = -\frac{g_A}{\left(1 + \frac{Q^2}{M_A^2}\right)^2}$$

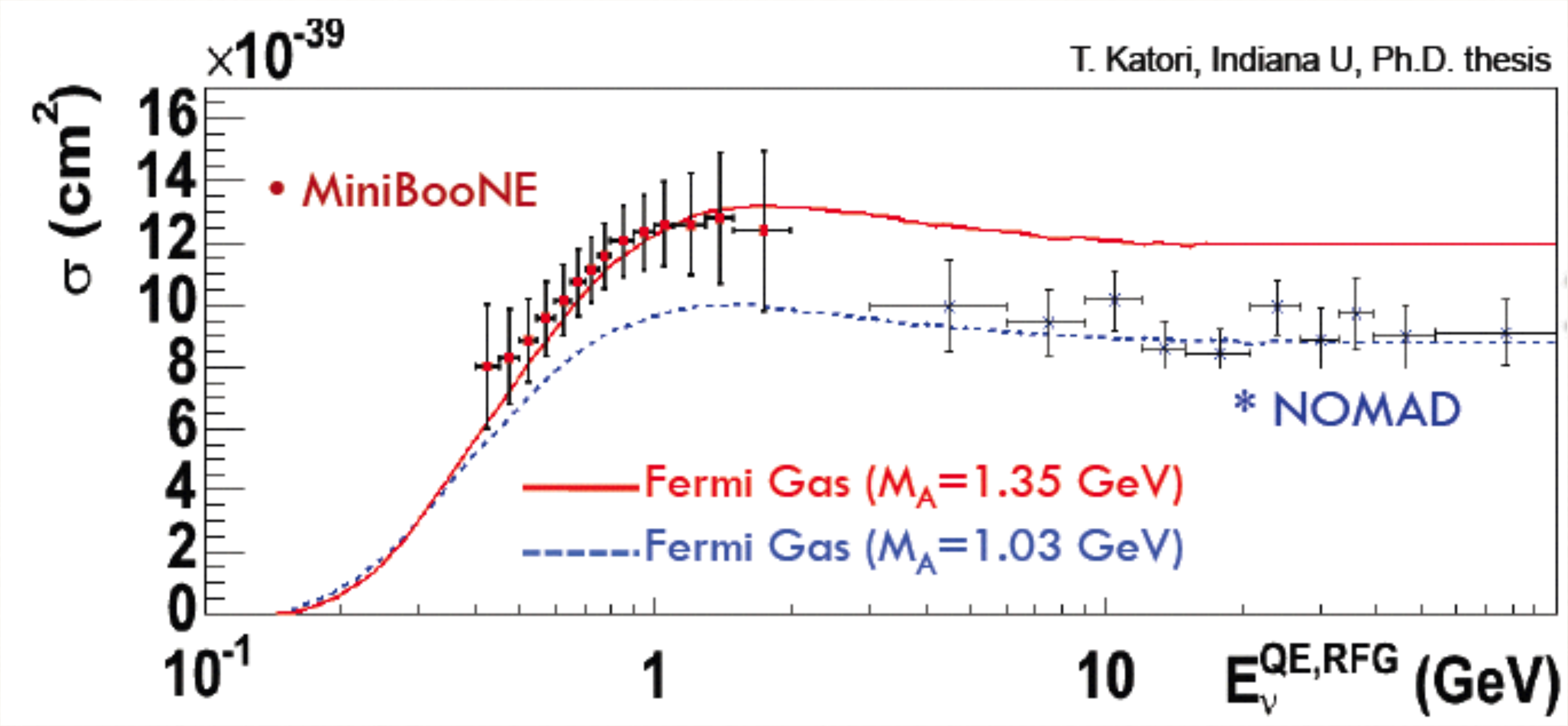
Known from beta decay

We are left with only one unknown parameter in the quasi-elastic form factor, an axial mass. It modifies both the Q^2 shape and total cross-section.

M_A has been measured a lot, often in Deuterium bubble chambers; as of 2003, experiments agreed that M_A is ~ 1 GeV

Recent Measurements of M_A

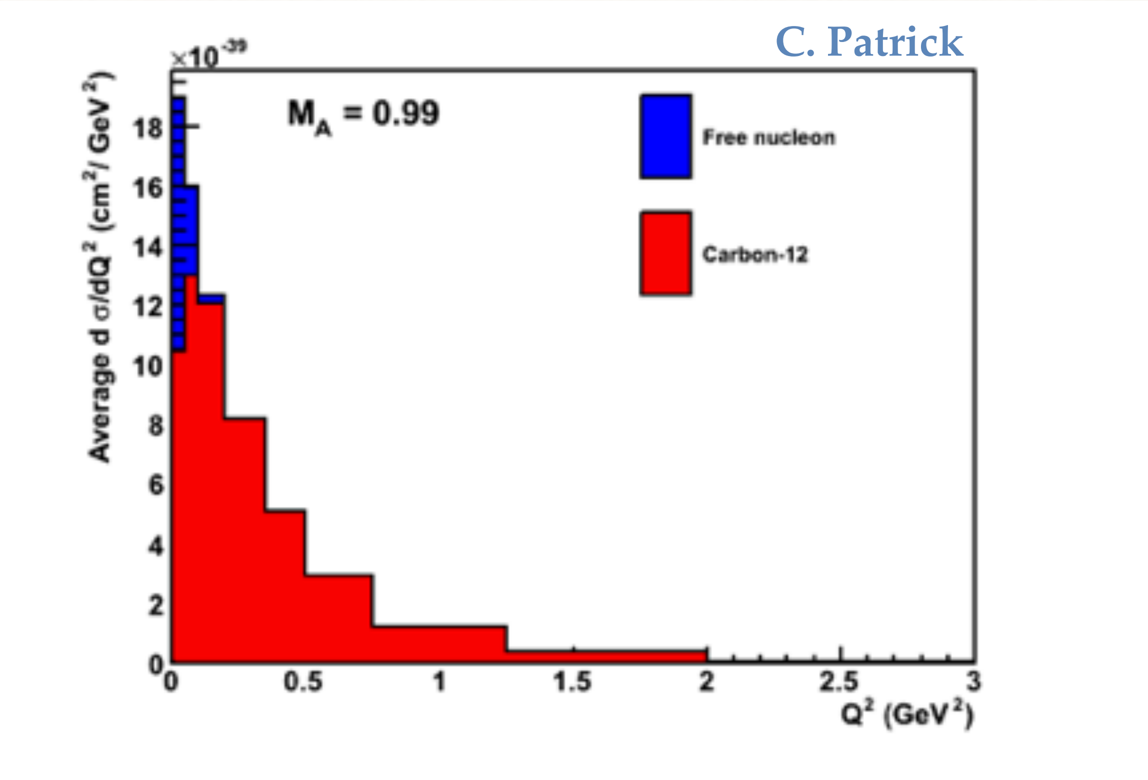
- The MiniBooNE experiment turned the view that quasi-elastics and M_A are well understood upside down:



The MiniBooNE data prefer a much larger axial mass than older experiments; this preference is supported by SciBooNE, K2K and MINOS

What's Going On?

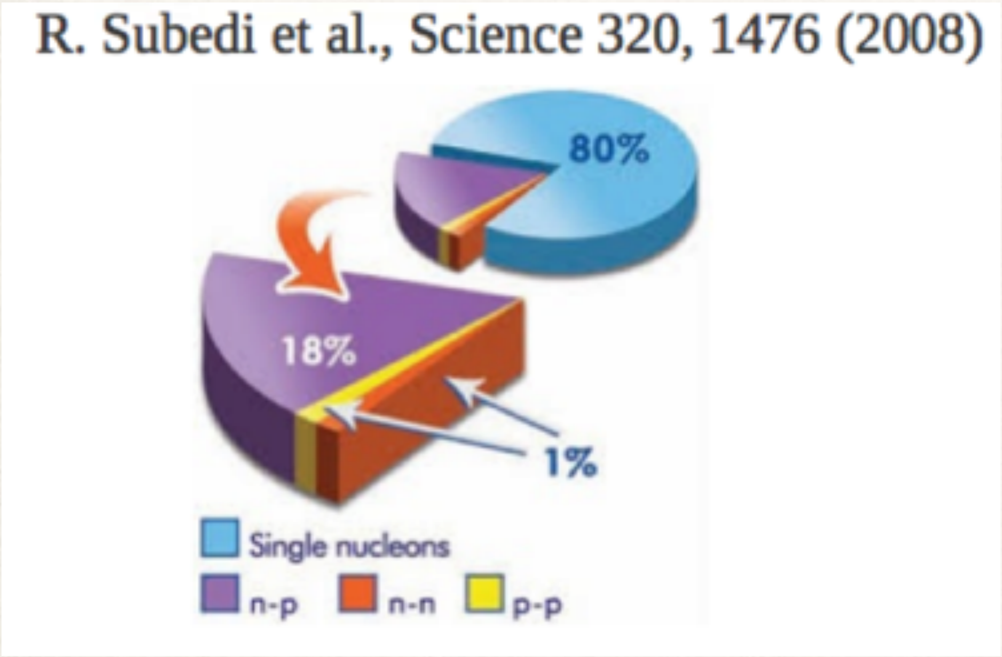
- One issue: everything I've told you so far applies to neutrino-nucleon scattering
- But modern neutrino detectors are made of heavy nuclei (which yield high event rates)
    - The nucleons within particle detectors are not free!



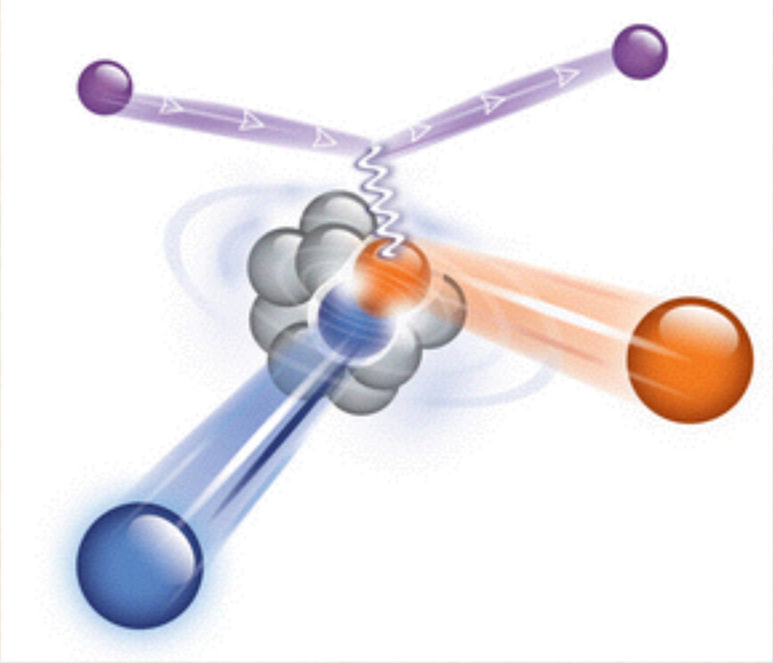
Some ways that the nucleus modifies the interactions:

Pauli blocking reduces the cross-section at low Q^2
Final state particles can interact as they exit the nucleus
Initial state nucleons have Fermi momentum → smears final state kinematics
Neutrinos can interact with multi-nucleon bound states

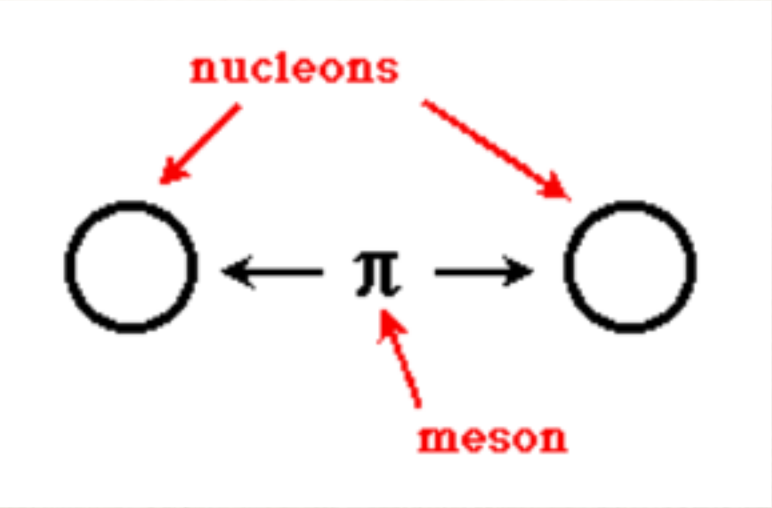
Multi-Nucleon Bound States



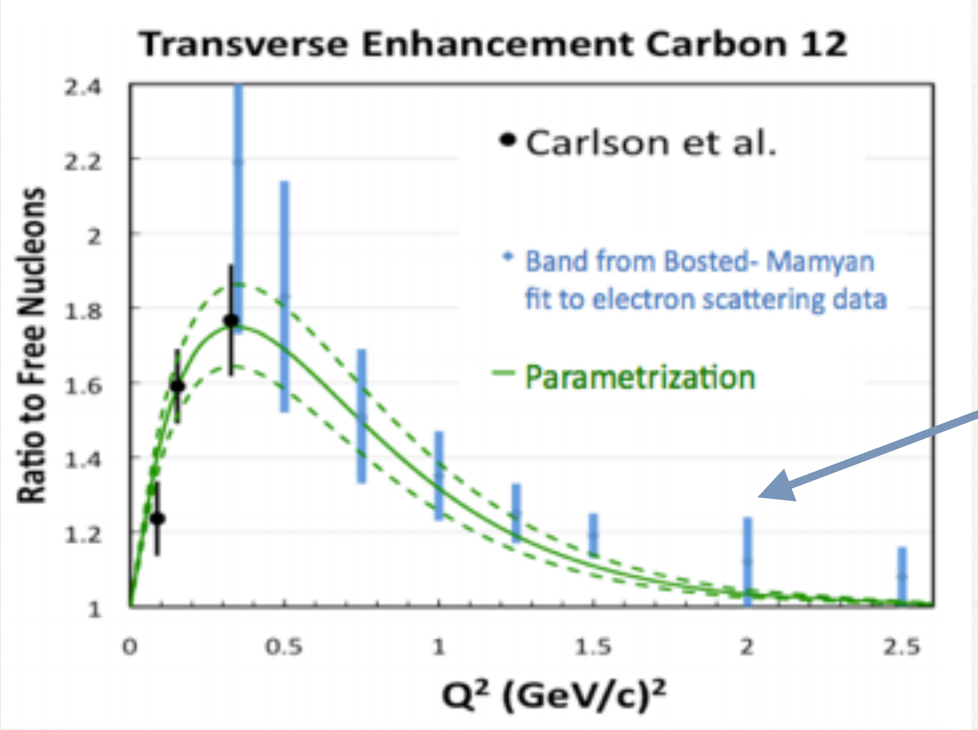
- We know from electron scattering that ~20% of nucleons are involved in **Short Range Correlations.**
- Other correlations known as **Meson Exchange Currents (MEC)** have also been hypothesized.



The impact of nuclear correlations on quasi-elastic (and other) neutrino scattering is **not well understood**, but there are indications that their **effects are substantial.**



Experimental hits of MEC

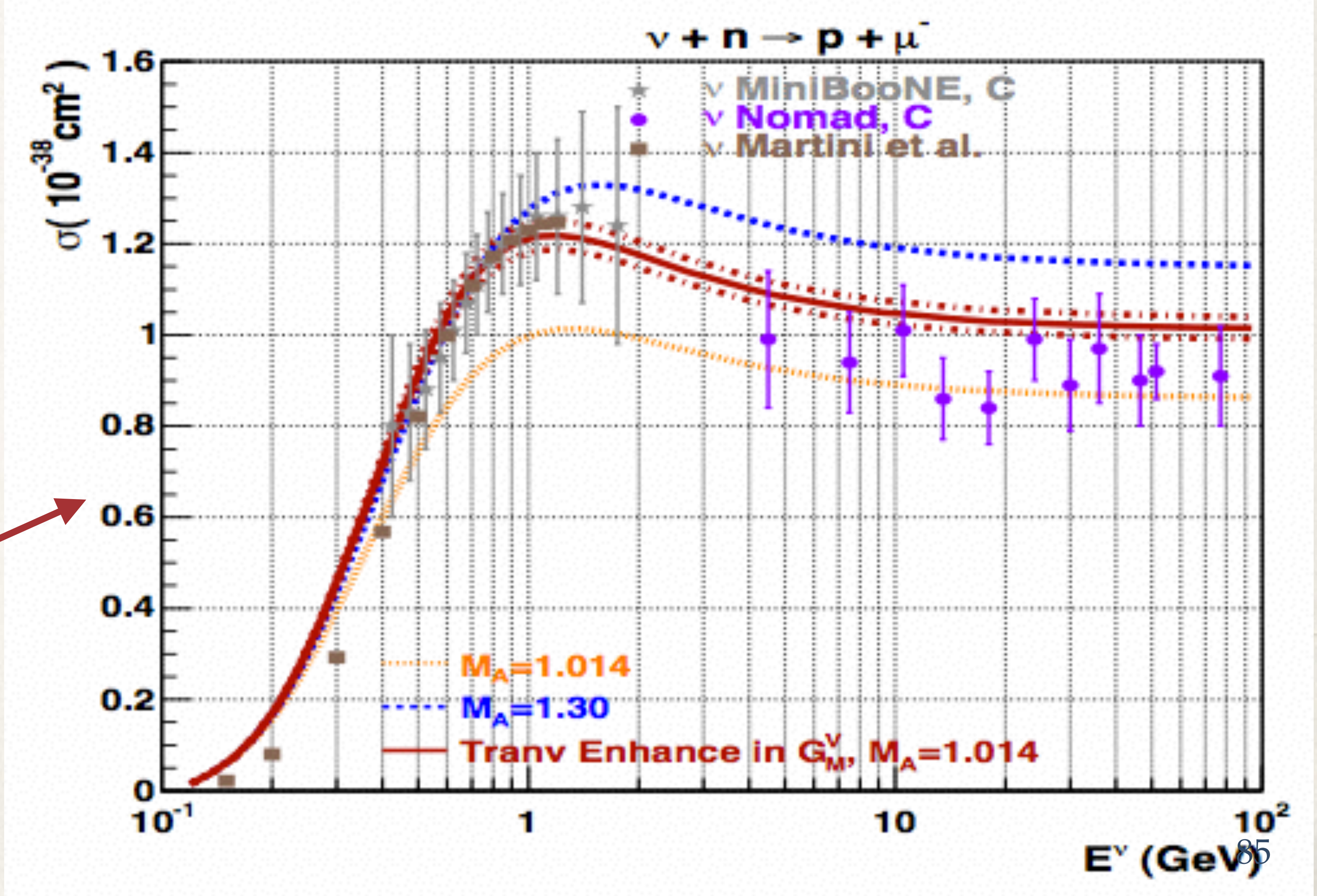


- An enhancement of the transverse component of the quasi-elastic electron scattering cross section on Carbon is thought to be due to Meson Exchange Currents

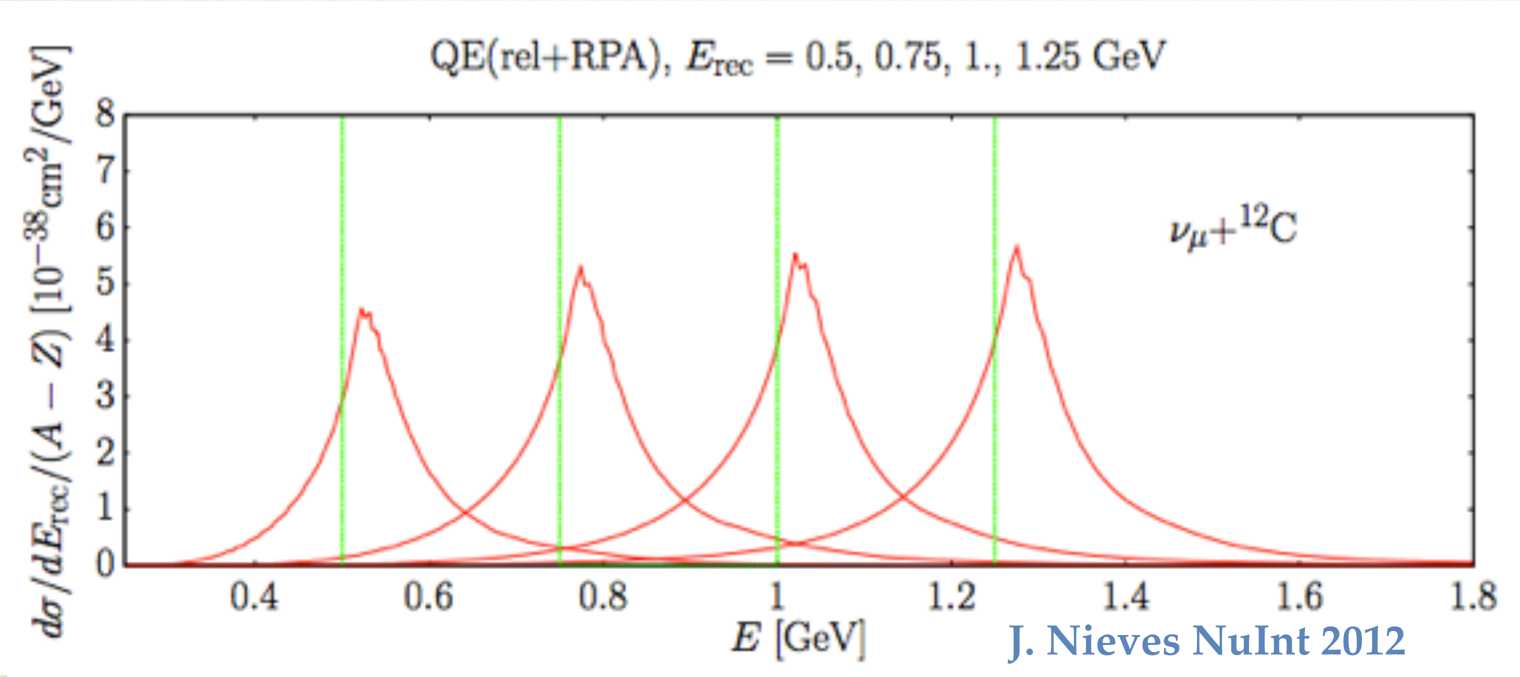
A. Bodek et al, Eur. Phys. J. C 71 (2011) 1726, arXiv:1106.0340

- This enhancement has been parameterized and used to predict a MEC contribution to neutrino scattering

- This transverse enhancement model (TEM) is a better fit to MiniBooNE and Nomad data than a modification of M_A



Impact of MEC on Oscillation Physics

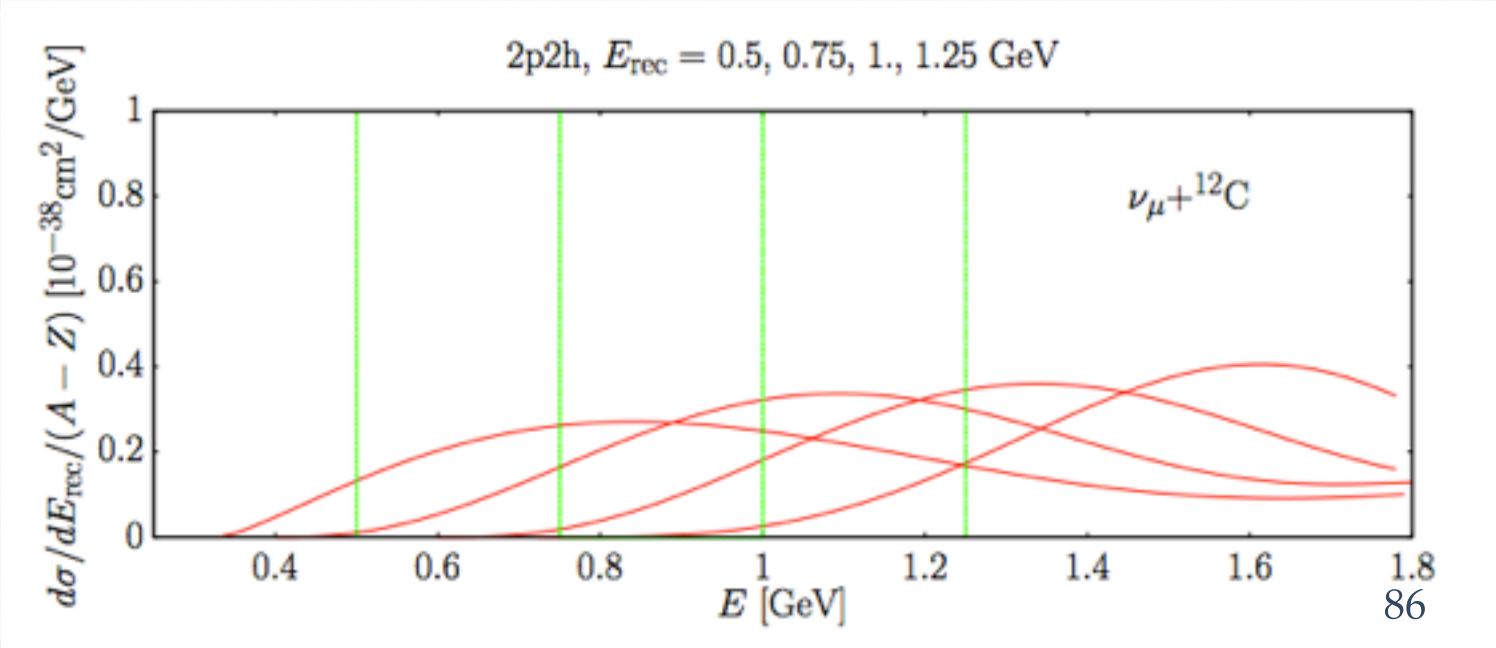


- Neutrino energy reconstructed assuming a quasi-elastic hypothesis is similar to true energy in standard quasi-elastic interactions

Reconstructed (green) and true (red) energy in traditional quasi-elastic scattering assuming perfect detector resolution

Reconstructed (green) and true (red) energy in Meson Exchange Current events assuming perfect detector resolution

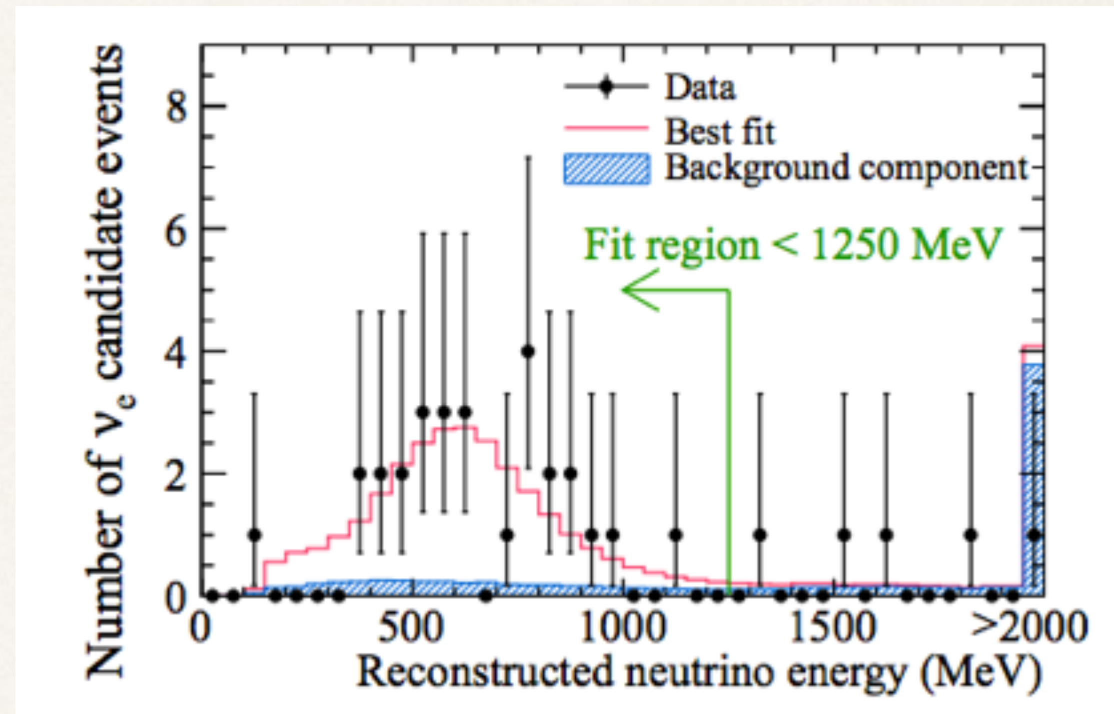
- Energy reconstruction using a quasi-elastic hypothesis does not work on MEC events.



More Impact on Oscillation Physics

Energy smearing from MEC is one small component of a large picture that must be understood to make high precision oscillation measurements:

The need for precision neutrino scattering measurements is very clear from T2K's most recent ν_e appearance measurement



arXiv:1311.4750v1 [hep-ex]

interactions. Parameters in the second category are typically related to the interaction target—primarily carbon at ND280 and oxygen at SK—and include Fermi momentum, binding energy, and spectral function modeling for the CCQE nuclear model. Also in this category are normalizations for other CC and NC cross sections, the ν_e/ν_μ CC cross section ratio, pion production parameters, and final state interactions of pions exiting the nucleus. External data sets, primarily from [21–23], are used to determine the initial values and prior uncertainties of the parameters [4].

TABLE II. The uncertainty (RMS/mean in %) on the predicted number of signal ν_e events for each group of systematic uncertainties for $\sin^2 2\theta_{13} = 0.1$ and 0.

Error source [%]	$\sin^2 2\theta_{13} = 0.1$	$\sin^2 2\theta_{13} = 0$
Beam flux and near detector	2.9	4.8
(w/o ND280 constraint)	(25.9)	(21.7)
ν interaction (external data)	7.5	6.8
Far detector and FSI+SI+PN	3.5	7.3
Total	8.8	11.1

Summarizing the Quasi-Elastic Situation

- Understanding quasi-elastic interactions is **crucial for oscillation experiments**
- Scattering experiments have produced **contradictory cross section measurements** that indicate significant nuclear effects are present
- Theorists have postulated **QE-like processes** that would have big implications but have yet to be experimentally confirmed

Oscillation measurements are moving into a new era that will involve **high-precision measurements** and searches for **subtle effects**.

A much clearer understanding of quasi-elastic interactions will be necessary for this next generation to succeed.

The MINERνA detector was designed to make this happen.